THE STUDY OF INFLUENCE OF GEOMAGNETIC FIELD ON EXTENSIVE AIR SHOWERS

A. BHASKARA RAO

1962.

ABSTRACT

The work described in the thesis is concerned with "The Study of Influence of Geomagnetic Field on Extensive Air Showers". An attempt is made to verify experimentally the idea of ellipticity of shower structures suggested by Cocconi.

In the first chapter a brief review of the present ideas about cosmic radiation is presented. The Nucleonic-cascade model of Extensive Air Showers is described qualitatively, right from the origin at the top of the atmosphere till the showers reach the surface of the earth including the lateral spread of showers.

In chapter II the experimental arrangement is described with the help of figures. A brief description of the necessary precautions that have been observed in the preparation of reliable counters with long platean and similar characteristics is given. The electronic circuitary used in the experiments is also shown.

In chapter III Cocconi's prediction that the deflection of air shower particles in the earth's magnetic field should produce some ellipticity of shower structure, and his theoretical calculations of the geomagnetic effect are

presented. The experimental results obtained at Gulmarg (alt: 2710 m) while investigating this prediction are analysed and discussed. The results are also compared with those of Chaloupka, Dubinsky-Chaloupka, Norman and Nikolsky-Satsevich. The qualitative agreement of the results is pointed out. Some drawbacks of the experimental arrangement and the extent to which they affect the observed geomagnetic effect are discussed. It is concluded that the geomagnetic field has a significant influence on the lateral distribution of shower particles.

Chapter IV contains the experimental results collected at Aligarh (alt: 205 m). The discrepancy between the experimentally observed geomagnetic effect by several authors and the theoretically predicted value of Cocconi is pointed out. Oren's theoretical calculations for the influence of geomagnetic field on various components of Extensive Air showers: a) primary particles b) π-mesons c) μ-mesons and d) their decay electrons are given. The results collected at Aligarh are compared with those of Oren at Haifa. The influence of altitude on the geomagnetic effect of Extensive Air Showers is also discussed.

In Chapter V the directional properties of shower detecting arrays are discussed. The significant differences between the results of various authors regarding the directional efficiency of Extensive Air shower arrays are pointed out. Possibilities of further improving the performance of the device are also indicated.

The papers published on the work presented in the thesis are also attached in the end.

The results present in the thesis suggest, at least qualitatively, that the geomagnetic field has considerable influence on the lateral distribution of shower particles, and the ellipticity of shower structure is more than the theoretically predicted value of Cocconi.

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THE STUDY

OF

INFLUENCE OF GEOMAGNETIC FIELD ON EXTENSIVE AIR SHOWERS.

A. BHASKARA RAO

1962.

A thesis submitted to the Aligarh Muslim University, in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Physics.

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The work reported herein was done under the supervision of Prof. P.S. Gill in the Department of Physics, Muslim University, Aligarh.

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ACKNOWLEDGEMENTS

While submitting this thesis, I welcome the opportunity to express my profound and heartfelt gratitude to Prof. P.S. Gill, M.S. (So. Calif.) Ph.D. (Chicago), F.N.I., whose invaluable guidance and kind attention I have enjoyed throughout the course of the work. I am highly grateful to Dr. H.S. Hans for his kind interest in the progress of my work. My warmest thanks are due to the staff and scholars of the Gulmarg Research Observatory for their many genial gestures and helpful suggestions while working at Gulmarg.

I thank the technical staff of the Department for their competent assistance in running the experiments. My thanks are particularly due to Mr. Ajit Singh, the Glass Blower, for his liberal cooperation in preparing all the necessary G.M. Counters.

Finally I acknowledge with thanks, the financial support from the U.P. Research Committee, the Muslim University and the Department of Atomic Energy, which enabled me to carry out the investigations smoothly.

A. Bhaskara Rao.
Department of Physics
M.U. Aligarh.

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CHAPTER - I.

GENERAL INTRODUCTION:

A. PRIMARY COSMIC RADIATION.

It has been known for almost sixty years that the earth's atmosphere is under the continuous bombardment of an extremely penetrating radiation, called 'Cosmic Radiation', coming from regions very far away from the earth. Although cosmic rays were discovered as back as 1900, only in 1912 V.F. Hess for the first time suggested from his experimental results that they come from outside the earth's atmosphere. By 1926 the results of Hess & Kolhörster were conclusive and the extra-terrestial origin of cosmic radiation was accepted. The most outstanding properties of the cosmic radiation are 1) extremely high penetrating power 2) isotropic nature of the radiation 3) constancy w.r.t time 4) the composition and finally 5) the mechanism by which they are accelerated to such super-high energies as 10^{15-19} eV or more.

A new era of investigation was initiated around 1929 by the work of Bothe & Kolhörster with a new instrument, the Geiger-Müller Counter. Besides the G-M counter, the invention of many new experimental techniques such as ionization chamber, cloud chamber, nuclear emulsions, scintillation counter, spark counter and finally buble chamber, gave a powerful stimulus for extensive and very fruitful researches on this phenomenon during the last three decades.

Now it is well established that the primary cosmic rays impinging on the top of the atmosphere constitute a stream of stripped nuclei at various energy levels, reaching at least upto 10^{18-19} eV. These are broadly classified into the following groups: 1) protons 2) Alpha particles 3) Light nuclei ($3 \leq Z \leq 5$) 4) Medium nuclei ($6 \leq Z \leq 9$), and 5) Heavy nuclei ($Z \geq 10$). If the abundances are compared at the same energy per nucleon, protons, alpha particles and nuclei of $Z \geq 2$ occur roughly in the ratio 93:6:1. Although the absence of electrons and γ-quanta in the primary cosmic rays has been established with great accuracy (of the order of one percent) the presence of a certain fraction (of the order of several percent) of negatively charged heavy particles or antiprotons is not however ruled out.

During the last decade a vast amount of information has been collected regarding the particles of cosmic-radiation in the neighbourhood of the earth. Consequently we now have reasonably reliable information on a) the average intensity, b) the composition, c) the energy spectrum, d) the directional asymmetry and e) the almost complete absence of primary electrons. In spite of all this, we do not have a comprehensive theory for the origin of cosmic radiation, at present. This is one problem which is still defying the efforts of many eminent workers. Any theory of the origin of cosmic radiation has to account for the nature of the primary particles, how they acquire their super-high energies and why they appear to arrive at the top of the earth's atmosphere with equal intensity from all directions. Until recent times, many theories have been put forth by various authors; but no one theory has been able to explain all the important properties satisfactorily. However, during the last few years the super-nova origin of cosmic rays, first suggested by Baade and Zwicky (1934) has gained great popularity mainly due to the extensive work carried out in this branch by the Russian workers. So far this theory has been able to explain many of the important characteristics of the cosmic radiation, sometimes quantitatively and sometimes only qualitatively. There are still some serious difficulties which require further check and elucidation.

The analysis of the exceptionally valuable data that has been collected all over the world during the period of I.G.Y.(1957-59) may lead to a much more profound understanding of a number of important items of information on the nature of the cosmic-ray variations, the nature of correlation between the cosmic rays and the various geophysical and astrophysical factors This will establish not only an intimate relation between the science of cosmic-ray variations, on the one hand, and meteorology, geophysics, heliophysics and astrophysics, on the other hand, but will convert the study of cosmic-ray variations into a new powerful tool for the investigation of astrophysical phenomena.

B: <u>SHOWER PHENOMENON</u>.

Extensive Air Showers, abbreviated as EAS, is the name given to a very interesting cosmic-ray phenomenon. EAS are ascribed to the super-high energy component of the cosmic radiation (10^{13}-10^{19} eV), and manifest themselves by blanketing wide areas whose diameter is as large as several hundreds of meters, with thousands and even millions of time correlated particles, and consequently this fact facilitates us to observe such high-energy events, in spite of the very small frequency of the primaries initiating cosmic-ray showers. The shower particles are not associated merely by chance, but are genetically related to one another. The EAS are not distinct in any way from the general cosmic radiation but for the fantastic magnitude of the energy associated with the shower producing particles, of the order of 10^{15-19} eV. In fact it is yet to be established whether an upper limit exists to the energy of the primary particles in the cosmic radiation.

The first suggestion that a photon-electron cascade might be present in the earth's atmosphere appears to have been made independently by Blackott & Cloy. However, in 1937 Schmeiser and Bothe clearly pointed out that measurements of the Rossi transition curve always yield a positive intercept at zero thickness, and that this implies the occurrence of showers in the free air. Schmeiser and Bothe (1938) demonstrated that particles in showers had separations upto at least 40 cms; but within a short time Auger, Maze & Grivet-Meyer (1938) and Kolhorster, Mathes & Weber (1938) had measured coincidences between counters several tens of meters apart. The phenomena responsible for such coincidences have come to be known as 'Extensive Air Showers'.

By 1939 quite a good amount of experimental information about the EAS had already been accumulated, largely by the efforts of the paris group working with Auger. For instance, the decoherence curve had been measured out to 300 m, by Auger, Maze & Robley (1939). The experimental and theoretical researches carried out during the past two decades led to a fairly clear, though not complete, picture of the shower-phenomenon.

C: LATEST MODEL FOR EAS.

For several years after the discovery of the shower phenomenon, it was thought that the EAS, as distinguished from other cosmic-ray phenomena, represented the effects of primary electrons or photons of very high energy. The small numbers of mesons and nucleons in the EAS were considered to be secondary to the more numerous photons and electrons. However, due to the intense research work carried out on high-energy nuclear interactions during the period 1946-49 by flying balloons carrying nuclear emulsions to great heights in the atmosphere, it has been well established that EAS are a combination of a high-energy nucleonic cascade and electromagnetic cascade. It has been also established that there are practically no electrons or photons of high energy in the primary cosmic radiation. Although they are the most numerous elements of EAS at maximu development, it has become evident that the photons and electrons are themselves a secondary component, while the EAS are initiated and dominated in their development by the nuclear-active particles. Besides, it is now recognized that the EAS simply represent the common chain of events following the incidence of any high-energy proton or heavy nucleus on the top of the atmosphere. Another piece of experimental evidence which is vital to the problem was the production in high-energy nuclear collisions of π-mesons both charged and neutral, and the almost instantaneous decay of the neutral π-mesons into two γ-ray quanta. It was also found that charged π-mesons interact with nuclei in the same manner as fast protons, the competetion between nuclear interaction and spontaneous decay (into μ-mesons) depending upon the energy

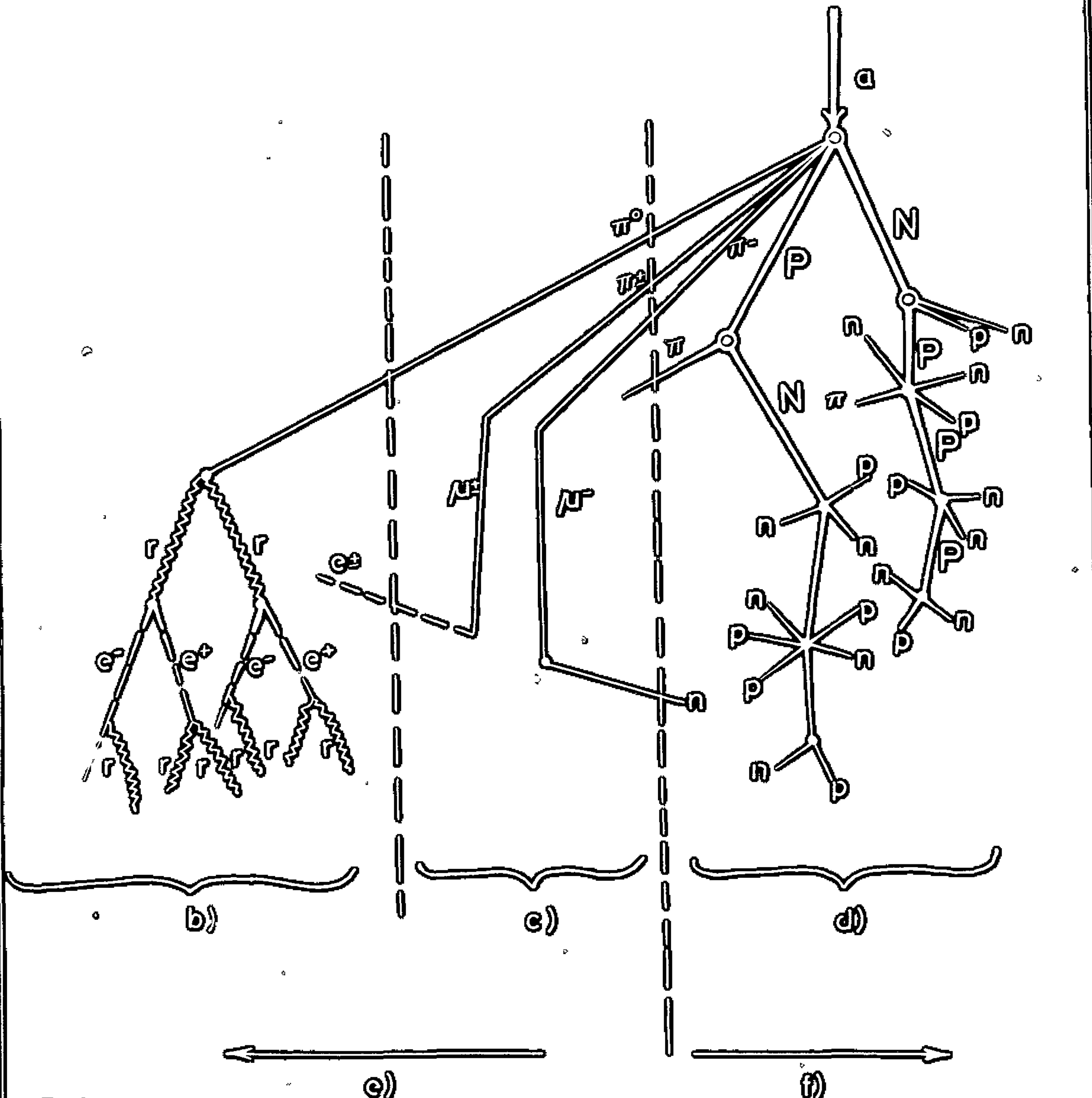

FIG.1 NUCLEONIC CASCADE MODEL OF EXTENSIVE AIR SHOWERS

N, P – High energy nucleons.
n p – Low energy nucleons of nuclear fissions.

a) – INCIDENT PRIMARY PARTICLE;
b) – ELECTROMAGNETIC (soft) COMPONENT;
c) – MESON (hard) COMPONENT;
d) – NUCLEONIC COMPONENT;
e) – PASSAGE OF ENERGY FROM NUCLEONIC TO ELECTROMAGNETIC INTERACTIONS;
f) – SMALL PORTION OF ENERGY IS RETURNED FROM THE MESONIC COMPONENT TO THE NUCLEONIC.

This information led to the development of a new model for the EAS called "Nucleonic cascade Model", as shown in Fig. 1. An incoming primary particle, either a proton or a complex heavy nucleus, striking an air nucleus at an altitude near 20 km, makes, within a time of the order of 10^{-23} sec (the time of travel of the nucleus) a series of collisions which may be either elastic or radiative. In the latter case, the air nucleus is disrupted thus initiating a cascade of nuclear interactions. These interactions give rise to a shower of mesons, charged as well as neutral, and nucleons which continue towards the earth almost along the projected axis of the incoming particle. The central region around the axis is usually called the 'core' of the shower. These axial particles produce further nuclear disintegrations giving rise to more mesons and nucleons, constituting the nucleonic cascade. The neutral π-mesons produced in the initial and subsequent collisions, decay into high-energy γ-rays, which in turn, initiate photon-electron cascades. Some of the charged π-mesons decay into μ-mesons which form a penetrating non-interacting component. The summation of all the individual cascades constitutes the EAS.

Radiation processes of electrons and materialization of photons combine to produce the so called cascade showers. The high-energy γ-rays produced in the decay of π^0-mesons will undergo materialization, giving rise to electron pairs.

When the electrons are incident upon matter, they will soon produce high-energy photons. Thus the number of particles (electrons and photons) rapidly increases as the radiation progresses through matter. At the same time, however, the average energy of the individual particles decreases until electrons are no longer capable of radiating photons and are eventually absorbed by ionization loss, and photons are no longer capable of producing pairs and after undergoing further degradation by Compton scattering, are finally absorbed by photo-effect. At this point the shower dies out.

The relative intensities of various components change rapidly as the radiation propagates through the atmosphere. Near the top of the atmosphere the primary radiation still predominates, and therefore most cosmic-ray particles are protons and neutrons (either free or bound in complex nuclei). The number of these particles decreases rapidly with decreasing altitude. At the same time the number of electrons and photons increases rapidly and goes through a maximum. In the region of the maximum, electrons and photons greatly out number all the cosmic-ray particles. Below the maximum, the electron-photon component too begins to decrease rapidly with decreasing altitude. Charged π-mesons disintegrate into μ-mesons and neutrinos. μ-Mesons interact with nuclei very weakly. Neither do they undergo radiation losses comparable to those of electrons, nor do they under go nuclear collisions as do protons or neutron

Therefore, they lose energy almost exclusively by ionization until they decay into electrons and neutrinos or until they reach the earth's crust and bury themselves underground. Thus the local cosmic radiation in the atmosphere contains protons, neutrons, π-mesons, μ-mesons, electrons and photons. π-mesons of course are very scarce everywhere in the atmosphere because of their short mean life(2.65×10^{-8} Sec)

It can be seen that an EAS consists of a core of high-energy penetrating particles, some of which are nuclear inter-acting (N-component) i.e., nucleons and π-mesons and some are high-energy μ-mesons and electrons. The abundance of these particles relative to electrons varies with distance from the axis of the shower. The electron-photon component and μ-mesons of relatively low energy are distributed around the core.

It is worthwhile to emphasize that while the picture presented above is almost certainly correct in its main features, it may well prove inaccurate in more than one important detail. For example, high energy nuclear inter-actions may give rise to photons directly as well as through the intermediary of neutral π-mesons. It is also possible that V-particles and other unstable particles heavier than π-mesons, which were neglected, may play a significant role in the chain of events, accompanying the propagation of cosmic rays through the atmosphere. Similar remarks can be made about the presence in the nucleonic cascade of antiprotons and anti-neutrons, production of which must occur at these great energies. Nevertheless, it is believed at present that, even allowing for these, the conclusions drawn about the EAS would not be seriously altered.

D. PRESENT AND FUTURE PROBLEMS IN EAS.

After all, the immense interest manifested in the study of EAS is entirely understandable. Now there are machines which serve as laboratory sources of particles with energies upto 28 BeV. Before too long machines which can accelerate particles upto 100 BeV will be ready. Hence for a long time to come the EAS will retain their monopoly over the energy region beyond 10^{13} eV. Although the recent experimental researches have shown many phenomenological features of EAS, viz., the size-frequency distribution, the zenith angle distribution, the absorption coefficient in the atmosphere, the lateral distribution of electron-photon component, μ-mesons and the nucleon component at sea level and mountain altitudes and so on, many interesting questions still remain to be answered by future explorations, such as time variations and the charge of the primary particles that initiate largest of the air showers. There are two principal motives for continued study of EAS: first, to gather information related to the origin of the primary cosmic rays, and secondly, to investigate the nature of the interactions of extremely energetic particles. In fact the complex phenomena of EAS are only the source of information on the properties of particles with energies exceeding 10^{15} eV. Apart from that, the primaries that have energies exceeding 10^{15} eV, are expected to differ from the much more abundant particles of comparatively low energy; and observation of the differences may shed light not only on the problem of the origin of cosmic rays but also on various astrophysical matters.

Although it becomes clear that the EAS are understood as the combination of a high-energy nucleonic cascade, and electromagnetic cascade which is derived from the decay of π^0-mesons a unique model that can consistently explain all kinds of the experimental data has not been obtained yet. It must also be mentioned that the results of theoretical calculations so far obtained do not always correspond directly to the observations. Moreover, the experimental study of EAS has now reached the stage where possibly all the simple experiments have been done, and yet points of detail still remain obscure. That is why three big groups of scientists, namely the M.I.T. group, Harwell group and Moscow group are attempting to study various aspects of this phenomenon with almost gigantic shower detecting arrays.

Until recent times several elaborate calculations have been made by various authors to evaluate the lateral spread of EAS. But no body has taken into account the displacement from the rectilinear path, produced by the action of the earth's magnetic field, on the shower particles. They simply assumed the circular symmetry of the shower particles around the shower axis. Cocconi (1934) has evaluated, in the first approximation, the influence of the geomagnetic field on the electronic component and showed that the deflection of shower particles should produce some ellipticity of shower structure, with the major axis in the E-W direction, at least in the lower latitudes and at mountain altitudes. Results of the experiments conducted to verify this prediction indicate a much larger effect than suggested by Cocconi. Some experimental results obtained by the author on this effect were presented in the following chapters of this thesis.

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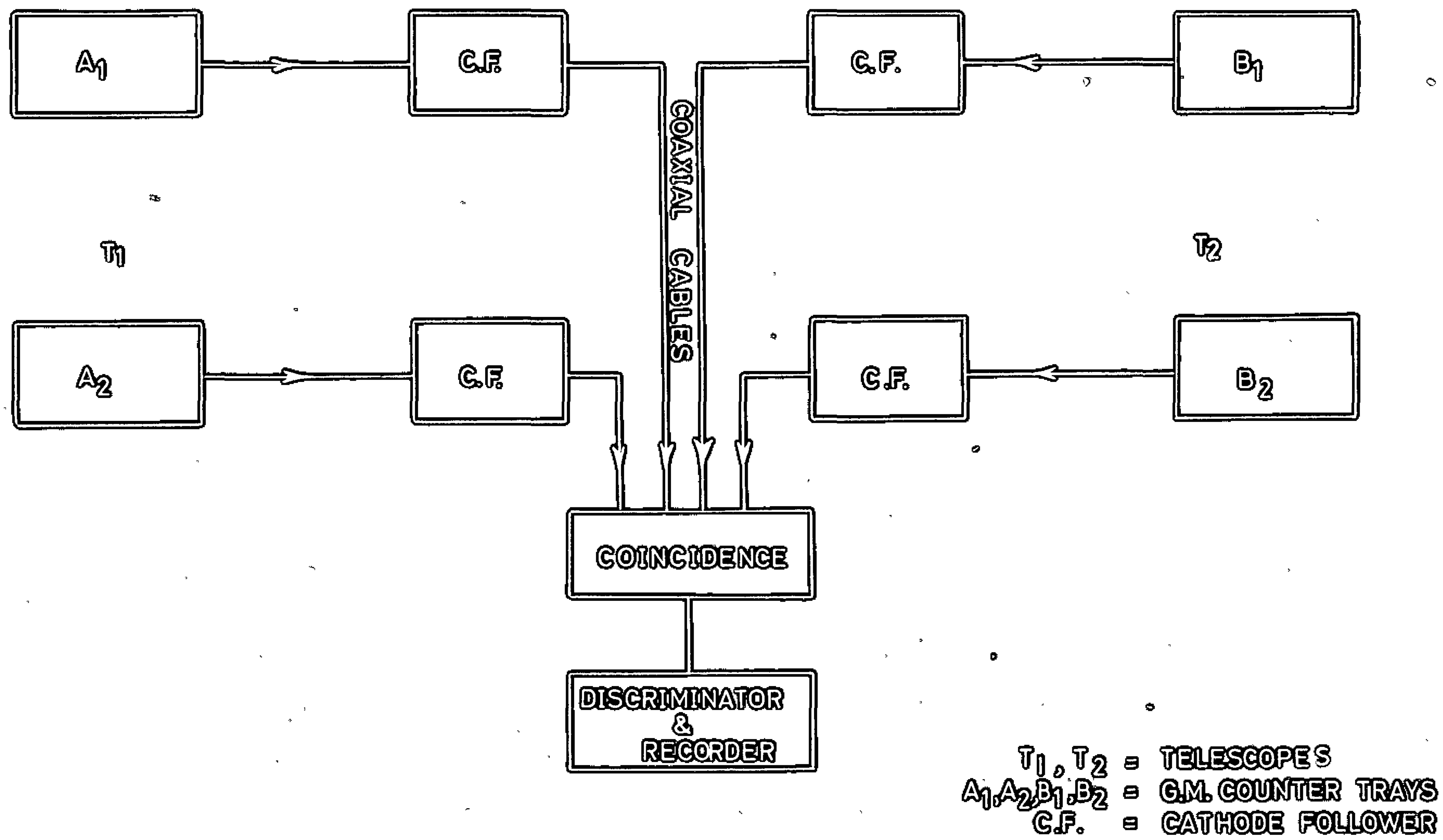

FIG.2 EXPERIMENTAL ARRANGEMENT

CHAPTER- II.

EXPERIMENTAL ARRANGEMENT.

The experimental arrangement shown by the block diagram of Fig.2 was similar to that of Chaloupka (1954). It mainly consisted of two G.M. counter telescopes, cathode follower circuits, discriminator and a recording circuit. The two telescopes (T_1 and T_2) were constructed by fixing two counter trays one above the other on an aluminium frame which was in turn mounted on a wooden stand. In each tray (A_1, A_2; B_1 and B_2) there were four counters (filled with Argon and petroleum-ether) connected in parallel. The separation of the counter trays in the telescopes was 950mm. The pulses from the trays were carried to the cathode-follower (C.F) and from there to the coincidence circuit, through low impedence coaxial cables type K·D-49. Only four fold coincidences were recorded by the electronic circuitory. The telescopes could be tilted independently around any axis and could be fixed at any zenith angle with the help of the protractor and needle attached to the telescopes.

The telescopes and the accessories were housed in tents to protect them from weather. G.M. counters only with a plateau of 200 v or more were used in the experiment. The counters were tested every day for their performance. Before fixing the telescopes at any particular zenith angle they were levelled with the help of a spirit level. All the power necessary for the regulated power supplies and the associated electronic circuitery was taken through a line voltage stabilizer to reduce the effects of the line voltage fluctuations to a minimum. All the G.M. counters necessary for the experiment were prepared in the Physics Department, Aligarh. A brief description of the preparation of counters and the associated electronic circuitery is given below.

PREPARATION OF G.M. COUNTERS.

The main guiding features for the preparation of G.M. counters are [Korpf (1953); Satyapal Puri (1956)] the simplicity of construction, ruggedness, low cost, high efficiency, longer plateau, small slope, photoinsensitivity and above all the reproducible and reliable operation and the absence of spurious counts. Further, in coincidence work large number of counters of exactly similar characteristics are needed. Self-quenching internal cathode type G.M. counters were used in the experiment. The above mentioned characteristics were achieved by following the steps listed below.

1) A copper cylinder of dimensions 23" length and $1\frac{1}{2}$" diameter made out of 40 s.w.g. copper sheet formed the cathode and a tungsten wire of 3 mil diameter served as the anode. The copper cylinder was inserted in a pyrex glass tubing of 2mm thickness. The ends of the glass cylinder were slightly rounded outward to reduce the field gradually and

the ends of the anode were shielded with insulating glass sleeves to avoid local fields and to limit the expansion of the sensitive volume beyond the ends of the cathode cylinder.

2) The counters were first cleaned with 6 N nitric acid to remove all surface contamination.

3) They were rinsed thoroughly with distilled water to remove any copper compounds formed by 6N nitric acid. Then 0.1 N dilute nitric acid was introduced and allowed to stay for few minutes.

4) They were rinsed thoroughly with distilled water for about 30 times to remove the last traces of the dilute acid.

5) They were dried under vacuum.

6) They were attached to a glass manifold which can be heated to any desired temperature from $0^{o}c$ - $400^{o}c$. They were subjected to the reduction process by passing hydrogen at least thrice at a pressure of 10 cm. Hg, maintaining the whole assembly at a temperature of $350^{o}c$.

7) Then they were oxidised in an atmosphere of commercial O_2 at a pressure of 10cm Hg and a temperature of $250^{o}c$, till a thin uniform brownish black deposit of CuO was formed on the surface of the cathode. This would increase the work function of the cathode surface and reduce the undesirable double pulses.

8) The counters were evacuated for several hours to ensure the removal of all water vapour and occluded gases, using Cenco Hyvac pump and oil-diffusion pump. To be very sure, the assembly was outgassed by roasting them for about an hour at 150°c under hard vacuum.

9) The central wire was flashed under vacuum to effectively remove microscopic bits of dust, lint, metal or sharp points on the wire, which give rise to spurious counts if they were not removed. This process also drives off the occluded gases and contributes to the chemical stability.

10) The counters were flushed with pure argon. The petroleum-ether vapour was introduced first and then the inert constituent, argon, in the ratio of 1:9 respectively to a total pressure of 10 cm Hg.

11) After filling the counters, they were allowed to stay on the assembly for about an hour for the diffusion equilibrium to be achieved.

12) Lastly both the ends of the counters, upto the extremeties of the cathode, were coated with Japan-black to reduce the photosensitivity of the counters. This will also give the glass surface a high resistance and reduces the formation of surface films of moisture or surface leakages.

The counters thus prepared and filled had a threshold of about 1000 v and a plateau of 200 - 250 volts

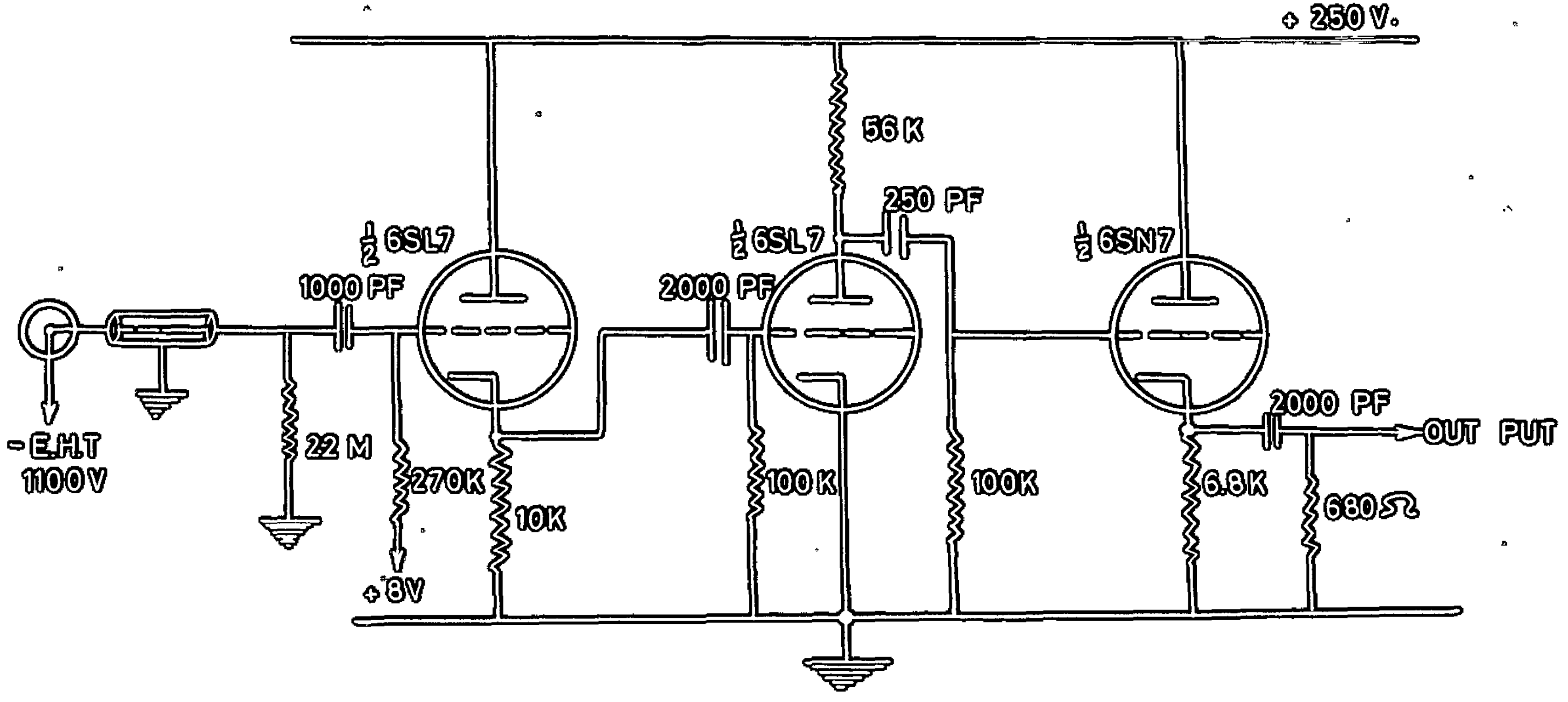

FIG.3

CATHODE FOLLOWER CIRCUIT

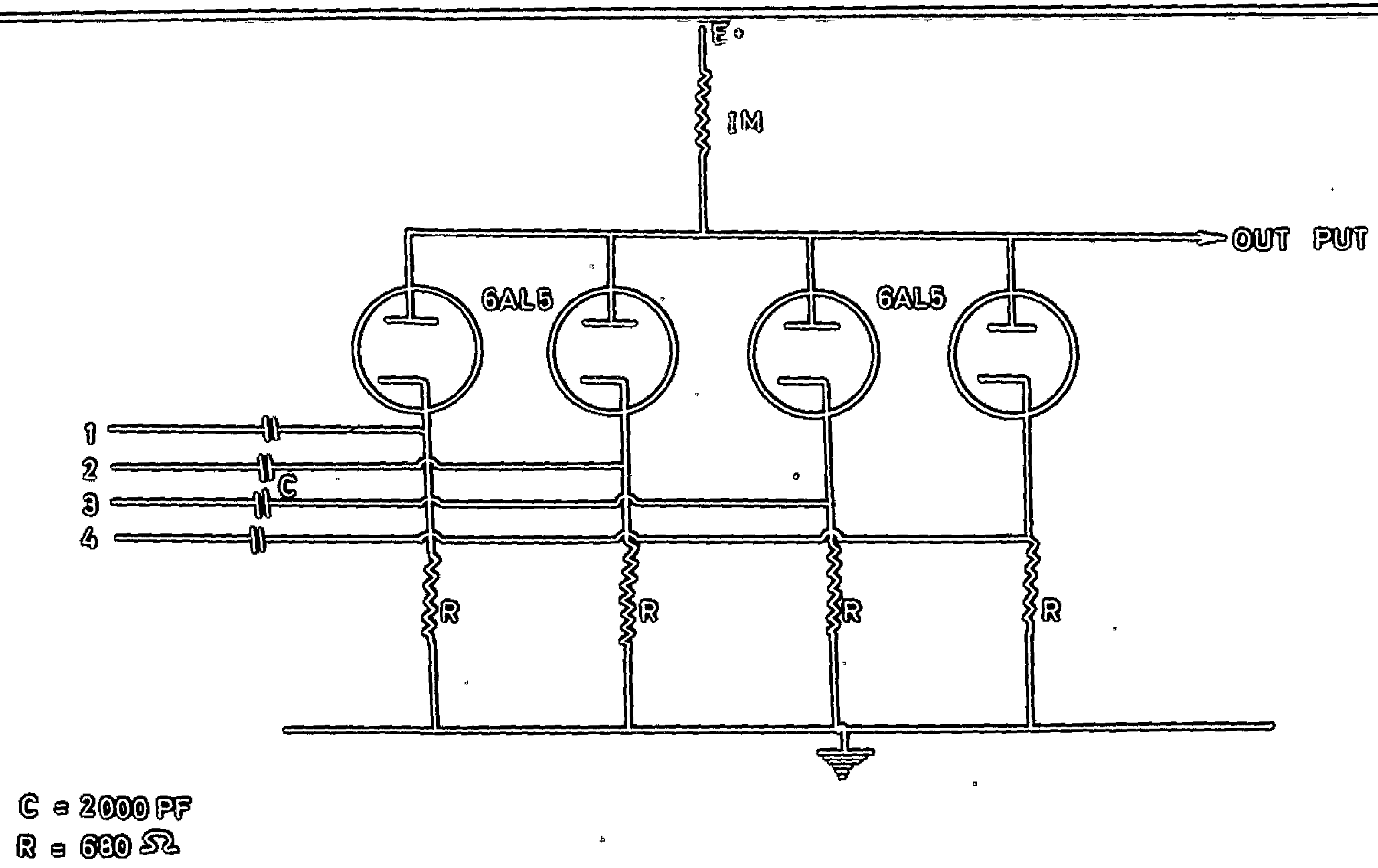

FIG. 4 COINCIDENCE CIRCUIT

with a small slope. The counting characteristics of these counters were also found to be independent of temperature within the range 32°c to 150°c [Puri & Gill, (1956)]. However, the contribution of the variations in counter temperature to the coincidence rate is very insignificant, particularly in view of the fourfold coincidences recorded.

ELECTRONIC CIRCUITARY:

For experiments with G.M. counters some form of input circuit is usually required for supplying a low impedance signal to the coincidence circuit. Cathode followers have the desired input and output impedances. The G.M. counter pulses were applied to the cathode follower circuit before they were taken to the coincidence circuit through low impedance coaxial cables. The cathode follower circuit [Howland et al., (1947)] consisted of an input cathode follower, an amplifier, a differentiating circuit and an output cathode follower, as shown in Fig. 3. The signal will be amplified and differentiated to give a pulse of approximately 5 μ sec duration. The output cathode follower supplies a low impedance positive pulse to the diode coincidence circuit.

The diode coincidence circuit [Howland et al.,(1947)] was shown in Fig.4. positive pulses from several signal sources were applied to the cathodes of the diodes. When the cathodes of 2 or 3 diodes are driven positive the remaining diode will carry the current which remains substantially constant and the

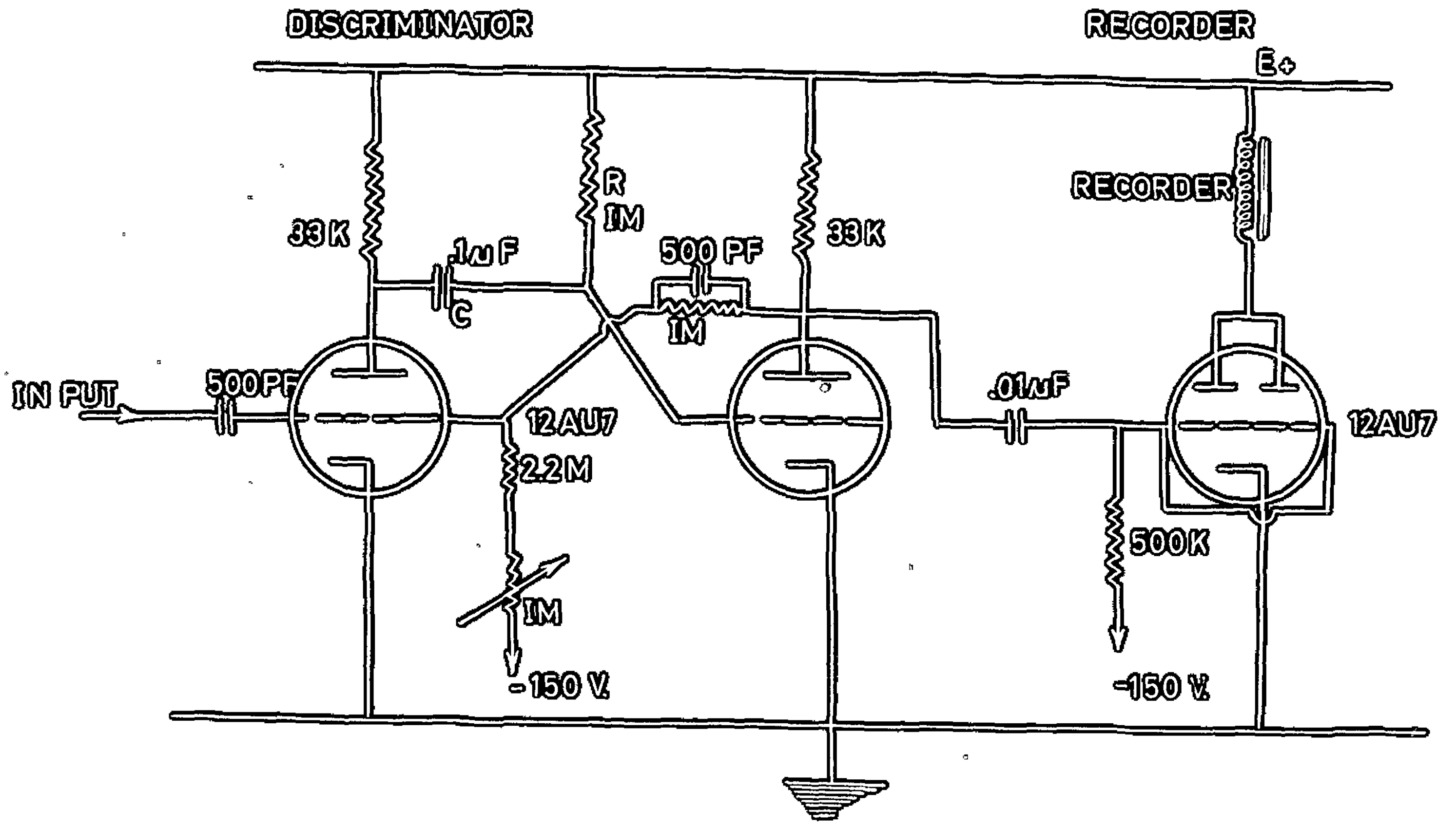

FIG.5 DISCRIMINATOR AND RECORDER

rise in plate voltage is extremely small. When, however, all the cathodes are driven coincidently positive, the plates will rise in potential and a sizable +ve output will be obtained which is supplied to the grid of the discriminator.

A plate coupled monostable multivibrator [Millman and Taub, (1956)] was used as the discriminator, Fig.5. Normally the left half of the multivibrator remains nonconducting and the right half fully conducting. Whenever a coincidence positive pulse comes on to the grid of the multivibrator, the left half of the tube flips over to conduction and the right half to the non-conducting condition and consequently a large constant voltage positive pulse appears at the plate of the right half of the discriminator. The multivibrator remains in this quasi-stable state for only a finite time determined by the values of R and C and then flips back to the stable state till the next coincidence pulse arrives. The positive output pulse from the discriminator was utilized to trigger the recording circuit.

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CHAPTER - III.

GEOMAGNETIC EFFECT ON EXTENSIVE AIR SHOWERS AT MOUNTAIN ALTITUDES.

ABSTRACT

Cocconi pointed out for the first time that the deflection of air shower particles in the earth's magnetic field should produce some ellipticity of shower structure, and hence the lateral distribution of electrons around the shower axis should not be circular, but elliptical, with the major axis in the geomagnetic East-West direction. Some authors tested this prediction experimentally and found a very large effect when compared with the theoretically predicted value. This effect has also been investigated at Gulmarg (alt. 2710m: 24°-36' N- geomagnetic lat.,) with two G.M. counter telescopes, for three separations 10 m, 25 m and 40 m. The results are in good agreement with those of others and show that there is a significant difference between the shower rates from East-West and North-South directions. The asymmetry in the shower rates is found to increase with the separation, and the zenith angle of the telescopes. An attempt is made to explain this behavior. Some drawbacks of the experimental arrangement and their effects on the observed geomagnetic effect are discussed. Qualitatively it is concluded that at least at mountain altitudes and low latitudes the geomagnetic field has quite a significant influence.

INTRODUCTION

Extensive Air showers are ascribed to the super high-energy component of the cosmic radiation. Shower initiating primary particles have energies exceeding 10^{15} eV. These high-energy primary particles are expected to differ from the much more abundant particles of comparatively low energy, during their passage through the earth's magnetic field, before reaching the point of observation. The assumption that the effect caused by the deflection of the shower initiating primary particles in the earth's magnetic field is negligible in the region of EAS energies, is quite reasonable. But the same assumption does not hold good for the shower particles of secondary nature, whose energies are very low when compared to that of the primary.

Since the discovery of EAS in 1939, up to date, several elaborate calculations have been made by many authors to determine the lateral distribution of the densities of electrons, μ-mesons, and nuclear-active particles in EAS, in the lower part of the atmosphere. In almost all the theoretical calculations and experiments on EAS, the azimuthal symmetry is assumed and the role of the geomagnetic field on the shower particles has been completely over looked by all the authors, without exception. Cocconi (1954) was the first to point out that the displacement from the rectilinear path produced by the action of the earth's magnetic field on the secondary electrons (±) of EAS cannot be negligible in comparison with the displacement due to coulomb scattering. He suggested that this lateral dispersion of electrons should produce some ellipticity of shower structure and hence lines of equal density should be stretched into roughly elliptical lines, with the major axis in the geomagnetic East-West direction. Physically this means that the electrons are distributed elliptically, around the shower axis, but not circularly.

THEORY OF THE EXPERIMENT.

The earth's magnetic field may be represented, to a good approximation, by the field of a dipole with its axis inclined at an angle of 11.8° to the axis of rotation of the earth, which passes at a distance of 342 km from the centre of the earth. In the equatorial plane it is horizontal and its intensity is equal to M/R^3; where $M=8.1 \times 10^{25}$ gauss cm^3, magnetic moment of the earth and $R=6.4 \times 10^8$ cm, the radius of the earth. This geomagnetic field acts on the arriving charged shower particles like a magnetic analyzer and deflects them either towards the East or west depending upon the sign of their charge.

Cocconi calculated only the deflection of electrons in the geomagnetic field. Electrons arise in an EAS in electron-photon cascades generated by γ-quanta from the decaying π°-mesons, which are produced in the elementary acts of nuclear cascade process. He calculated in the first approximation, the ratio of Dm, the displacement of air shower particles due to the earth's magnetic field to Ds, the projected lateral displacement due to multiple coulomb scattering. Since most of the EAS fall on the earth with small zenith angles° he considered only the influence of the horizontal component of the magnetic field°°, H=0.31 cos λ, where (λ) is the geomagnetic latitude.

The radius of curvature of an electron of energy E (mc^2)

becomes $$\rho = \frac{1.08 \times 10^{-2} E}{\cos\lambda} \text{ cm (E in eV)} \quad \ldots \quad (1)$$

When the displacement Dm is small in comparison with the path length (T) of the charged particle, as it is always in air;

$$Dm = \int_0^T (T-t) \; dt/\rho \qquad \ldots (2)$$

With sufficiently good accuracy Ds, the projected lateral displacement due to multiple coulomb scattering, which is

---

° Because of the I-cos$^n\theta$ relation for showers, nearly 80% of the showers fall within $\pm$ 30° to the vertical. The value of n varies between 3-9 depending on the altitude of observation.

°° In fact the displacement due to the earth's magnetic field is a function of both zenith and azimuth angles.

supposed to be the main phenomenon responsible for the distribution of electrons around the core of EAS is given by

$$\left\langle D_s^2 \right\rangle = \frac{1}{2} E_s^2 \int_0^T \frac{(T-t)\,dt}{E^2 X} \qquad \ldots (3)$$

where E_s = 21 Mev

X = 3x $10^4/P$, the characteristic radiation length in air, and

P = air pressure in atmospheres.

using equations (2) and (3) he arrived at the ratio as

$$\frac{Dm}{Ds} = \frac{0.48 \cos\lambda}{P} \quad \text{for} \quad \alpha T > 1 \qquad \ldots (4)$$

where α = log 2/x.

From the equation (4) it can be seen that up to quite high latitudes the separation of negative electrons from those of the positive ones due to the earth's magnetic field is quite comparable to the average lateral displacement of electrons due to coulomb scattering. Further, this effect increases with altitude of observation because of (P) in the denominator. From this equation he concluded that, at latitudes lower than 50^0 and around sea level the lateral distribution of particles of vertical showers is not circular, but elliptical, with the major axis in the East-west direction and almost two times larger than the minor axis and the effect should be large enough to be detected as an asymmetry in the lateral density distribution of electrons around the shower core.

However, two corrections were suggested by Prof. K. Greisen, to these calculations, [Cocconi (1954)]:

(a) Greisen pointed out the fact that an electron of a certain sign can have had parents of different sign before reaching the detecting apparatus, which decreases Dm by a factor of about 2. Then it follows that,

$$D_m/D_s = \frac{0.22 \, Cos\,\lambda}{P} \text{ instead of } \frac{0.45 \, Cos\,\lambda}{P} \quad \ldots (5)$$

Equation (4) remains valid for other shower particles.

(b) He also suggested that in evaluating the root mean square lateral displacement in the E-W direction, Dm must be added to Ds quadratically, but not linearly, as was implicitly done by Cocconi and this will reduce the ratio of the E-W to N-S lateral displacement further. The combined displacement due to the earth's magnetic field and coulomb scattering is,

$$D_{m+s} = \left[D_m^2 + D_s^2\right]^{1/2} \quad \text{so that}$$

$$D_{m+s} = D_s\left[1+\left(\frac{0.22 \, Cos\,\lambda}{P}\right)^2\right]^{1/2}$$

$$\simeq D_s\left[1 + \frac{0.02 \, Cos^2\lambda}{P^2}\right] \quad \ldots (6)$$

From this final equation it follows that at sea level the effect becomes practically negligible, of the order of about 2%, though it remains important however at higher altitudes.

The deviations from the circular symmetry are presumably insignificant for electrons below the critical energy (84.2 Mev in air). These electrons cannot travel very far in the air and are instead carried away from the axis of the shower mostly by single large-angle scatterings and hence the magnetic deflection becomes negligible in comparison with that due to multiple coulomb scattering.

Cocconi felt that probably the magnetic field of the earth does not affect the distribution of nucleons and mesons of an EAS. He suggested that the large angles at which these particles are emitted are mainly responsible for their lateral displacement, much larger, by one or two orders of magnitude in comparison with that produced by the earth's magnetic field and hence can be neglected. Although this statement is correct in the case of π-mesons, it is not true for μ-mesons, as discussed in the next chapter.

From the foregoing theory, Cocconi concluded that the geomagnetic deflection modifies quite strongly the distribution of high-energy electrons around the core of EAS, and to a smaller extent that of low energy ones. This modification in the shower structure, from circular symmetry to elliptical symmetry, will complicate the analysis of experiments on the density distribution of high-energy electrons around the core

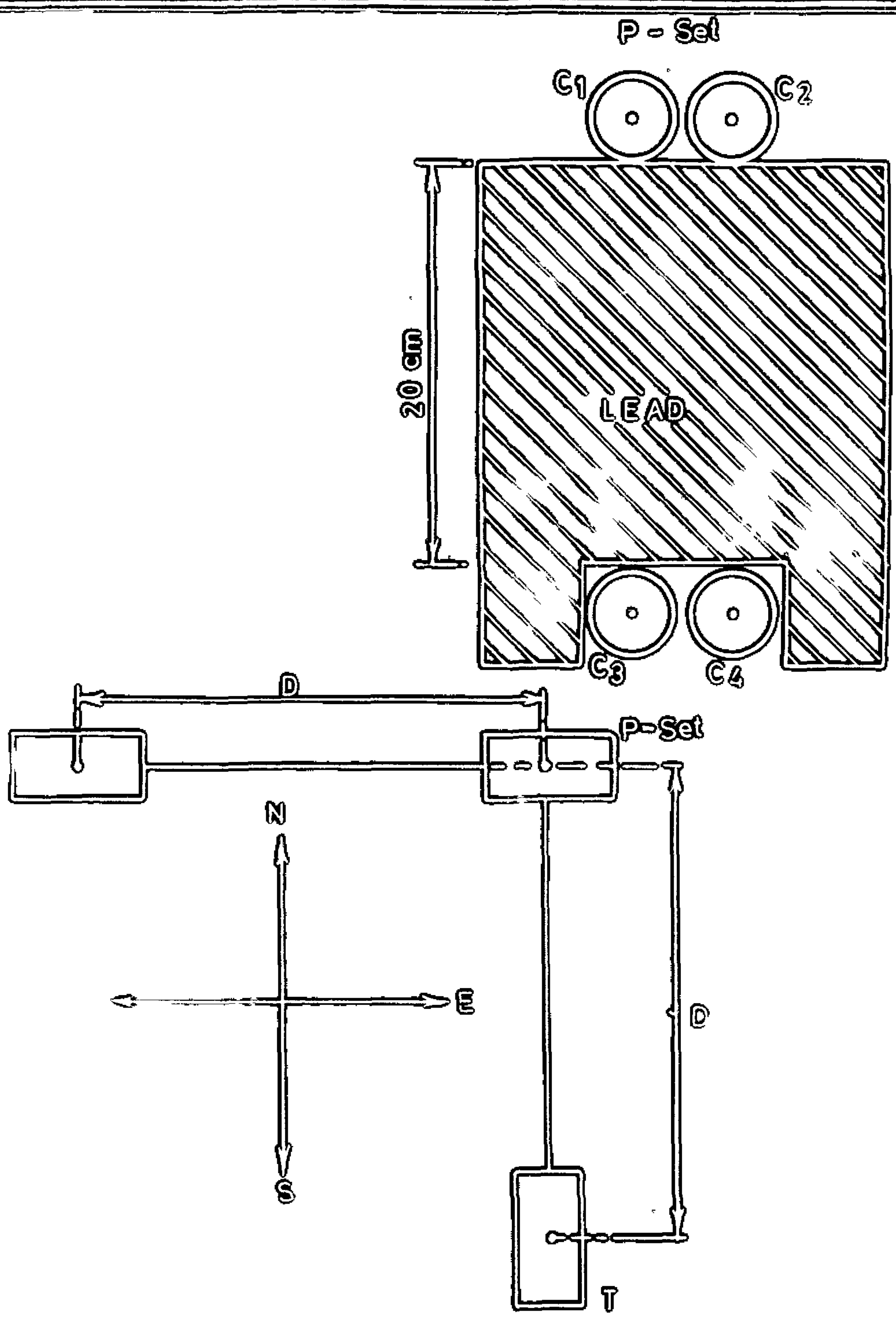

FIG.6 FROM DUBINSKY – CHALOUPKA, et al.(1956)

of EAS, and in general all experiments whose interpretation depends on the electron lateral distribution.

RESULTS AND DISCUSSION:

P. Chaloupka (1954) investigated for the first time, Cocconi's theoretical prediction of the influence of geomagnetic field on EAS, on the top of "Lomnicky' stit" (alt. 2634 m; 48° N. geomagnetic latitude) with two G.M. counter telescopes of approximately 18° semi angle each. The separation of the telescopes was 7 m. The telescopes were inclined at 45° zenith angle and successively directed towards East, West, South and North. Fourfold coincidences were taken. His results, given in Table -I, show nearly 20% more showers arriving from the East-West direction than from North-South direction. Due to the large statistical errors and inadequate data, he did not draw any conclusion. Later, Dubinsky, Chaloupka et al., (1956) continued the investigation with a different experimental set up (alt. 1778 m; 48° N. geomagnetic latitude) in which they fixed up the position of the shower core, using G.M. counters (Fig. 6) separated by 20 cms of lead, and measured the particle densities to the West & South of the core, at three distances i.e., 15.5 m. 30 m. and 50 m. Although they could not find any variation in density for 15.5 m separation, they observed 40% and 60% greater densities in the west direction than in the south for 30 m and 50 m distances respectively, Table II. The

TABLE - I.

Experimental results of Chaloupka (1954).

Separation between telescopes: 7m.

Zenith angle 'Z'	Coincidence rate per hour from			
	East	West	South	North
45°	45.2 ±2.9	50.1 ±2.6	38.5 ±2.3	38.3 ±2.3

TABLE - II.

Experimental results of Dubinsky, Chaloupka et al (1956).

Distance from the core of the shower in meters 'D'	Coincidence rate per hour from	
	South $N_s \pm \sigma_s$	West $N_w \pm \sigma_w$
18.5	1.49 ± 0.15	1.34 ± 0.17
30.0	0.96 ± 0.11	1.37 ± 0.15
60.0	0.59 ± 0.09	0.96 ± 0.14

observed effect was abnormally large compared to the theoretically predicted value. However, even in this case the statistical errors were quite large.

The present investigation was carried out at Gulmarg (alt. 2710 m : 24°-36' N. geomagnetic latitude) a suitable place to study this effect in view of the moderate latitude and considerable altitude of the place, with improved statistics. The experimental arrangement was already described in detail in the preceding chapter. The experimental set up was just similar to that of Chaloupka. It mainly consisted of two G.M. Counter telescopes of semi angle 12.4° each. The asymmetry in the rate of showers was measured for three separations between the telescopes i.e., 10 m, 25 m and 40 m. The telescopes were directed towards East, West, South and North at zenith angles 0°, 15°, 30°, 45° and 60° and fourfold coincidences were recorded. The data were collected during the period June '59 to October '59.

The results of the experiment are given in Table III for the three separations 10 m, 25 m and 40 m. In any direction if the total number of counts recorded is N, during the total time T in hours, then the shower rate from that direction is N/T per hour. The error in the shower rate is taken as $N^{\frac{1}{2}}/T$. The data are summarised in Table-IV. In Table-V the average shower rate from East-West directions is taken as (x) and the average shower

TABLE - III

Counting rates of showers from the EAST direction with corresponding errors.

Separation between telescopes	Zenith angle Z	Total number of counts M	Total time in hours T	Average counting rate per hour $N_e = M/T$	Probable error $\sigma_e = M^{\frac{1}{2}}/T$	Showers per hour from the east $N_e \pm \sigma_e$
	0°	1416	15	94.4	2.5	94.4 ± 2.6
	15°	1747	22	79.4	1.9	79.4 ± 1.9
10 m	30°	2129	30	69.5	1.5	69.5 ± 1.5
	45°	1569	26	60.4	1.5	60.4 ± 1.5
	60°	1477	29	50.9	1.3	50.9 ± 1.3
	0°	1001	17	58.9	1.9	58.9 ± 1.9
	15°	1039	21	49.5	1.5	49.5 ± 1.5
25 m	30°	1386	41	45.0	1.0	45.0 ± 1.0
	45°	1044	26	40.2	1.2	40.2 ± 1.2
	60°	1015	29	35.0	1.0	35.0 ± 1.0
	0°	652	17	38.4	1.5	38.4 ± 1.5
	15°	684	21	32.6	1.2	32.6 ± 1.2
40 m	30°	654	22	29.7	1.2	29.7 ± 1.2
	45°	637	24	26.5	1.0	26.5 ± 1.0
	60°	686	28	24.5	0.9	24.5 ± 0.9

TABLE -III (continued)

Counting rates of showers from the WEST direction with corresponding errors.

Seperation between telescopes.	Zenith angle Z	Total number of counts M	Total time in hours T	Average counting rate $N_\omega = M/T$	Probable error $\sigma_\omega = M^{\frac{1}{2}}/T$	Showers per hour from the West $N_\omega \pm \sigma_\omega$
	0°	1416	15	94.4	2.5	94.4 ± 2.5
	15°	1792	22	81.5	1.9	81.5 ± 1.9
10 m	30°	1500	20	75.0	1.9	75.0 ± 1.9
	45°	1520	23	66.1	1.7	66.1 ± 1.7
	60°	1567	27	58.0	1.5	58.0 ± 1.5
	0°	1001	17	58.9	1.9	58.9 ± 1.9
	15°	1043	19	54.9	1.7	54.9 ± 1.7
25 m	30°	1012	21	48.2	1.5	48.2 ± 1.5
	45°	1039	23	45.2	1.5	45.2 ± 1.5
	60°	1002	27	37.1	1.2	37.1 ± 1.2
	0°	652	17	38.4	1.5	38.4 ± 1.5
	15°	635	18	35.3	1.3	35.3 ± 1.3
40 m	30°	652	20	32.6	1.3	32.6 ± 1.3
	45°	648	22	29.5	1.2	29.5 ± 1.2
	60°	673	26	25.9	1.0	25.9 ± 1.0

TABLE - III (continued)

Counting rates of showers from the South direction with corresponding errors.

Separation between telescopes.	Zenith angle Z	Total number of counts N	Total time in hours T	Average counting rate per hour $N_s = N/T$	Probable error $\sigma_s = N^{\frac{1}{2}}/T$	Showers per hour from the South $N_s \pm \sigma_s$
	0°	1480	17	87.0	2.3	87.0 ± 2.3
	15°	1730	24	72.1	1.7	72.1 ± 1.7
10 m	30°	2016	32	63.0	1.4	63.0 ± 1.4
	45°	1560	29	52.9	1.3	52.9 ± 1.3
	60°	1643	36	45.6	1.2	45.6 ± 1.2
	0°	1103	21	52.5	1.6	52.5 ± 1.6
	15°	1000	25	40.0	1.3	40.0 ± 1.3
25 m	30°	1061	32	33.2	1.0	33.2 ± 1.0
	45°	1016	36	28.2	0.9	28.2 ± 0.9
	60°	1030	46	22.4	0.7	22.4 ± 0.7
	0°	629	21	30.0	1.2	30.0 ± 1.2
	15°	641	26	24.7	1.0	24.7 ± 1.0
40 m	30°	638	31	20.6	0.8	20.6 ± 0.8
	45°	663	40	16.5	0.6	16.5 ± 0.6
	60°	640	48	13.3	0.5	13.3 ± 0.5

TABLE - III (continued)

Counting rates of showers from the NORTH direction with corresponding errors.

Separation between telescopes.	Zenith angle Z	Total number of counts M	Total time in hours T	Average counting rate per hour $N_n = M/T$	Probable error $\sigma_n = M^{\frac{1}{2}}/T$	Showers per hour from the North $N_n \pm \sigma_n$
	0°	1480	17	87.0	2.3	87.0 ± 2.3
	15°	1730	24	72.1	1.7	72.1 ± 1.7
10 m	30°	1591	26	61.2	1.6	61.2 ± 1.6
	45°	1720	32	53.8	1.3	53.8 ± 1.3
	60°	1660	35	47.4	1.2	47.4 ± 1.2
	0°	1102	21	52.5	1.6	52.5 ± 1.6
	15°	1056	26	40.6	1.2	40.6 ± 1.2
25 m	30°	1064	32	33.3	1.0	33.3 ± 1.0
	45°	1006	35	28.7	0.9	28.7 ± 0.9
	60°	1047	45	23.3	0.7	23.3 ± 0.7
	0°	629	21	30.0	1.2	30.0 ± 1.2
	15°	647	26	24.9	1.0	24.9 ± 1.0
40 m	30°	646	32	20.2	0.7	20.2 ± 0.7
	45°	642	39	16.5	0.6	16.5 ± 0.6
	60°	626	47	13.3	0.6	13.3 ± 0.6

TABLE - IV.

Average counting rates of showers from East, West, South and North directions with corresponding errors.

Separation between telescopes.	Zenith angle Z	Showers per hour from East $N_e \pm \sigma_e$	West $N_w \pm \sigma_w$	South $N_s \pm \sigma_s$	North $N_n \pm \sigma_n$
	0°	94.4 ± 2.8	- - - -	87.0 ± 2.3	- - - -
	15°	79.4 ± 1.9	81.6 ± 1.9	72.1 ± 1.7	72.1 ± 1.7
10 m	30°	69.8 ± 1.5	75.0 ± 1.9	63.0 ± 1.5	61.2 ± 1.5
	45°	60.4 ± 1.5	66.1 ± 1.7	52.9 ± 1.3	53.8 ± 1.3
	60°	50.9 ± 1.3	58.0 ± 1.5	46.6 ± 1.2	47.4 ± 1.2
	0°	58.9 ± 1.9	- - - -	52.6 ± 1.6	- - - -
	15°	49.5 ± 1.5	54.9 ± 1.7	40.0 ± 1.3	40.6 ± 1.2
25 m	30°	45.0 ± 1.0	49.2 ± 1.5	33.2 ± 1.0	33.3 ± 1.0
	45°	40.2 ± 1.2	45.2 ± 1.5	29.2 ± 0.9	28.7 ± 0.9
	60°	35.0 ± 1.0	37.1 ± 1.2	22.4 ± 0.7	23.3 ± 0.7
	0°	38.4 ± 1.5	- - - -	30.0 ± 1.2	- - - -
	15°	32.6 ± 1.2	35.3 ± 1.3	24.7 ± 1.0	24.9 ± 1.0
40 m	30°	29.7 ± 1.2	32.6 ± 1.3	20.6 ± 0.9	20.2 ± 0.7
	45°	26.5 ± 1.0	29.5 ± 1.2	16.5 ± 0.6	16.5 ± 0.6
	60°	24.5 ± 0.9	25.9 ± 1.0	13.3 ± 0.6	13.3 ± 0.6

TABLE- V.

Ellipticity and percentage asymmetry of EAS.

Separation between telescopes.	Zenith angle z	Average shower rate per hour from East- West $x \pm \sigma_x$	North-South $y \pm \sigma_y$	Ellipticity $\frac{x \pm \sigma_x}{y \pm \sigma_y}$	Percentage asymmetry $F = \frac{2(x-y)}{(x+y)} \times 100\%$
10 m	0°	94.4 ± 1.8	87.0 ± 1.6	1.09 ± .029	8.2 ± 2.6
	15°	80.8 ± 1.4	72.1 ± 1.2	1.12 ± .027	11.0 ± 2.4
	30°	72.3 ± 1.2	62.1 ± 1.1	1.16 ± .028	15.2 ± 2.4
	45°	63.3 ± 1.1	53.4 ± 0.9	1.19 ± .029	17.0 ± 2.4
	60°	54.5 ± 1.0	46.5 ± 0.9	1.17 ± .031	15.8 ± 2.7
25 m	0°	58.9 ± 1.4	52.6 ± 1.1	1.12 ± .036	11.5 ± 3.2
	15°	52.2 ± 1.1	40.3 ± 0.9	1.30 ± .040	25.7 ± 3.0
	30°	46.6 ± 0.9	33.3 ± 0.7	1.40 ± .040	33.3 ± 2.8
	45°	42.7 ± 1.0	26.6 ± 0.7	1.60 ± .051	39.9 ± 3.3
	60	36.1 ± 0.8	22.9 ± 0.5	1.58 ± .049	44.7 ± 3.0
40 m	0°	37.4 ± 1.1	30.0 ± 0.9	1.23 ± .053	24.6 ± 4.1
	15°	34.0 ± 0.9	24.8 ± 0.7	1.37 ± .053	31.3 ± 3.5
	30°	31.2 ± 0.9	20.4 ± 0.6	1.53 ± .063	41.9 ± 3.5
	45°	28.0 ± 0.8	16.5 ± 0.4	1.70 ± .064	51.7 ± 3.5
	60°	25.2 ± 0.7	13.3 ± 0.4	1.89 ± .078	61.8 ± 3.7

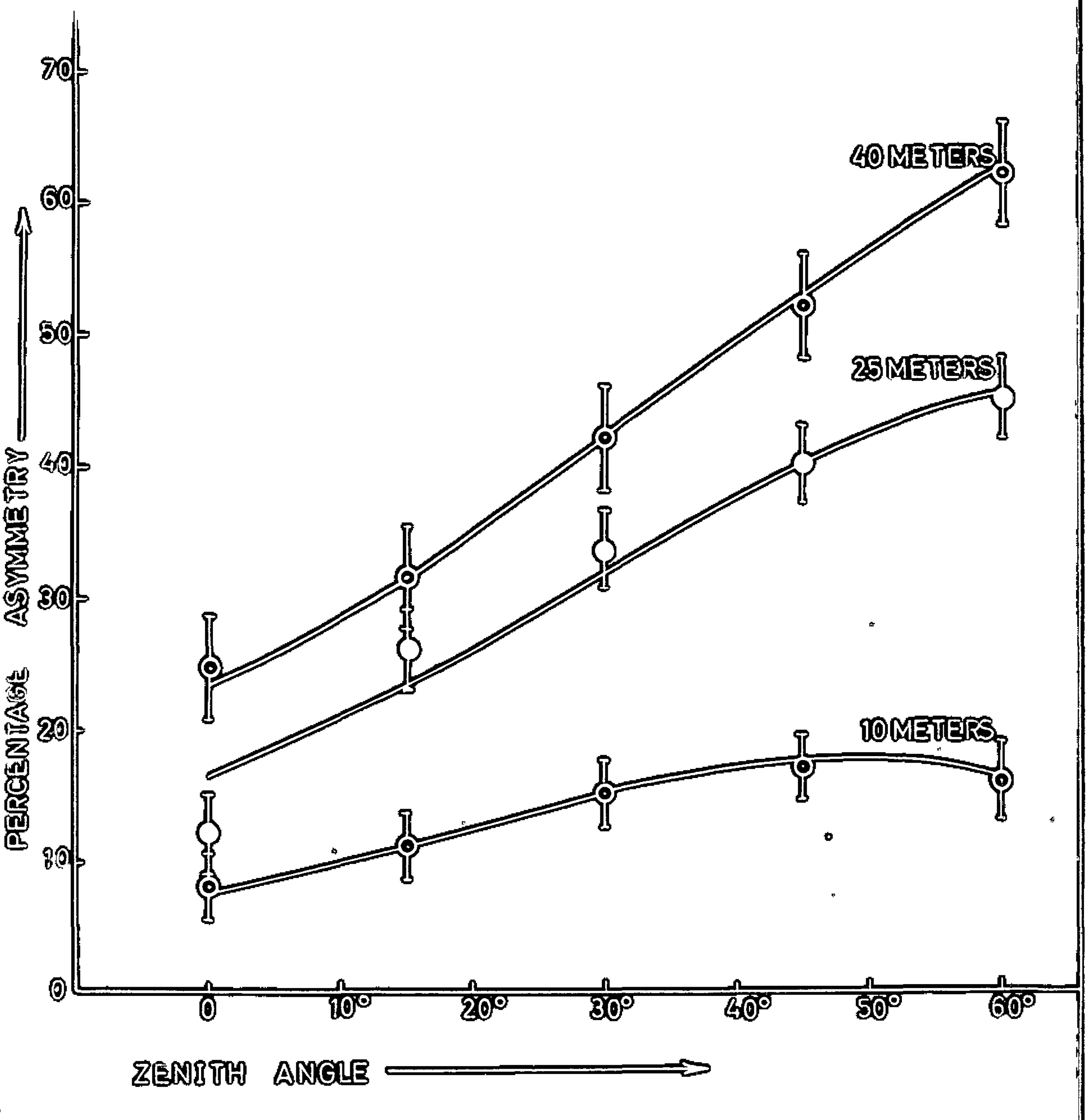

FIG.7 ZENITH ANGLE VS PERCENTAG ASYMMETRY

rate from North-South directions as (y). Next, the ratio (x/y) is calculated for the three separations and all zenith angles as shown. If the circular symmetry of the shower structure is to be correct, the ratio(x/y) should be unity. But from Table-V it can be seen that in all the cases, without exception, the ratio is larger than unity, and far beyond the statistical errors. This clearly indicates that electrons in EAS are distributed elliptically around the shower axis, but not circularly. The percentage asymmetry between the shower rates from E-W and N-S directions is given in the last column of Table-V.

The errors in the ellipticities and the percentage asymmetries are calculated as follows:

If (F) is a function of both (x) and (y) then the error in (F) is given by

$$\sigma^2 = \left[\frac{d(F)}{dx}\right]^2 \sigma_x^2 + \left[\frac{d(F)}{dy}\right]^2 \sigma_y^2$$

when (σ_x) and (σ_y) are errors in (x) and (y) respectively and (σ) is the error in the function (F).

Then a graph is drawn with the zenith angles along the abscissa and the percentage asymmetries along the ordinate for the three separations of the telescopes (Fig. 7). From the graph it is obvious that the asymmetry increases systematically with zenith angle. The asymmetry corresponding to 10 m separation goes on increasing upto 45° zenith and then shows a decreasing tendency between 45° and 60° zenith angle. But this downward tendency after 45° zenith angle seems to disappear gradually, for the other two curves. This increase in the asymmetry with zenith angle can be partly attributed to the increase in the path length of the particles in the earth's magnetic field. But somehow, the increase in the path length alone cannot explain the large increase in the asymmetries with zenith angle. The graph also indicates that at any particular zenith angle the asymmetry increases with the separation between the telescopes. According to Y. Oren (1969) this increase in the asymmetry with separation between the telescopes is due to the geomagnetic deflection of the μ-meson component of the EAS. This will be fully discussed in the next Chapter. Of course the same arguments hold good for ellipticity values also. The percentage asymmetry and ellipticity will increase by about 4 - 5% if the shower rates only from west and south are taken into consideration, since the average shower rate from E-W is less than the individual shower rate from West, though the shower rates from North or South are exactly the same.

According to Cocconi's theoretical prediction basing on electromagnetic cascade theory the geomagnetic effect should be about 2% at sea level and about 6% at mountain altitudes. But the effect observed experimentally, even upto 60% (Dubinsky, Cheloapka et al) was rather abnormally large. Experimental results collected at Gulmarg also suggest a very large effect in

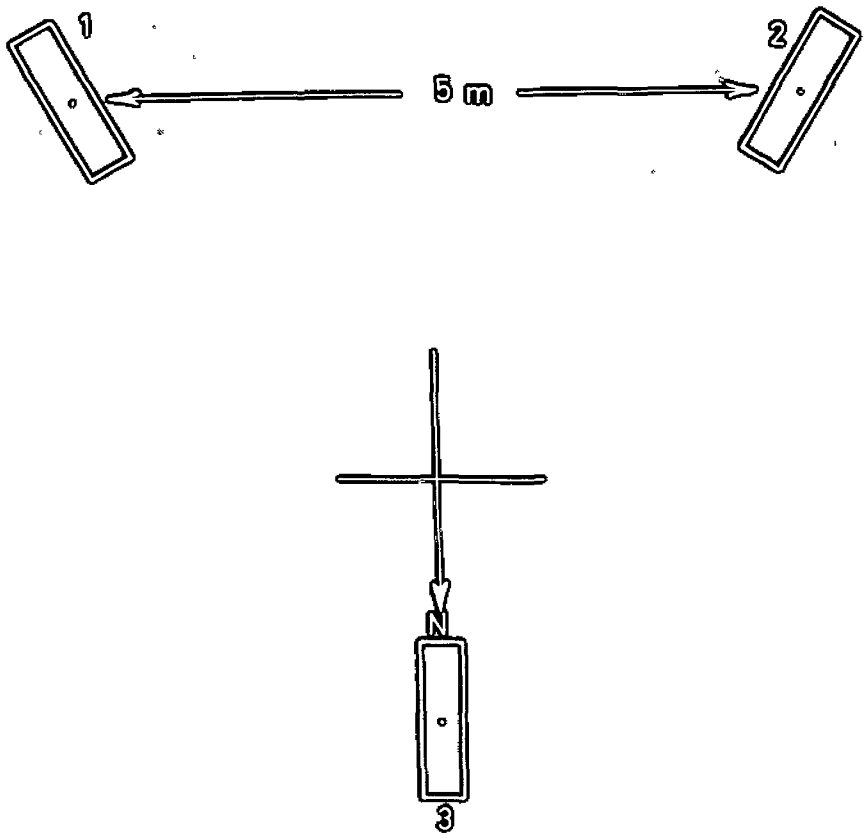

FIG. 8. FROM NORMAN, R. J., (1956)

comparison with the theoretical prediction. This discrepancy between the theory and experiments is yet to be explained. Our results are fairly in good agreement with those of Chaloupka and Dubinsky, Chaloupka et al. Though the experimental arrangements used are not exactly identical, the latitudes and altitudes are different, qualitative agreement between the results is quite obvious. The geomagnetic effect is quite large and inconsistent with the theory.

Norman (1956) and Nikolski & Satsevich (1956) also tested this prediction of geomagnetic effect, at sea level. Norman's experimental arrangement consisted of three proportional counters placed radially at the three corners of an equilateral triangle of sides 8 m each (Fig. 8). One side of this triangle was in the East-West direction, where the ellipticity is expected to be greatest. The remaining two sides lay in directions 30°E of and 30° W of North, thus recording substantially the effect in the N-S direction. The lateral structure function was observed to be the same in each of the three directions within the experimental error of 4%, suggesting that the effect of the earth's magnetic field on shower structure at sea level is negligible compared to coulomb scattering. The absence of the geomagnetic effect in this case is quite understandable. The experiment has been conducted at sea level and in the middle latitudes, 40°S. The most important thing is the separation between the counters. In this case it is so small that it is not possible to find any variation in the shower structure. Hence, even at sea level this experiment cannot be taken as conclusive, as to the existence or nonexistence of this effect.

Nikolski & Satacvich could not observe any effect for counters placed at 18 m from the centre of the shower, but when they were placed at 100 m, a small effect was found, corresponding to an increase in the radius of shower about 6-10% in the East-west direction. This observation is in contradiction with that of Cholaupka, Dubinsky-Cholaupka et al., and our own. Here again this difference can be attributed mostly to the difference in the altitudes of the places and to a smaller extent to latitude. The geomagnetic effect seems to be more sensitive to the altitude of the point of observation than predicted by the theory.

Moreover the theoretical calculations of Cocconi, even for electronic component, are only approximate. It is well known that most of the spreading of a shower in the lateral direction takes place only in the first two or three radiation lengths above the detecting apparatus. Cocconi contented that Dm converges rapidly when the path length T increases because the energy of the electrons increases rapidly with altitude. But at the same time it should be remembered that the mean free path also increases for electrons with altitude, because of the low density of the atmosphere. This increase in the mean free path will naturally lead to larger deflections in the magnetic field which become important compared with the small deflections due to scattering at high altitudes. It is not possible to evaluate the true value of geomagnetic effect of the electronic component without a precise knowledge of the energy spectrum of the electronic component of a shower. It can be easily seen that the geomagnetic effect on the individual showers will be higher than the statistical average effect observed in the above mentioned experiments, if there is a means to observe the particle densities in different directions, from the core of the shower for each shower separately.

However the G.M. Counter telescopic arrangement has got certain drawbacks though they are not serious and do not introduce any drastic changes in the interpretation of the results. The apparatus used is not an ideal one for the directional study of showers, mainly due to the not very high directional efficiency of the G.M. counter telescopes to detect showers in a preferred direction. The telescopes are susceptible to a certain extent (quantitatively, to what extent is not known) to be triggered by showers coming from angles other than the telescopic aperture. If one has to arrive at a quantitative value of the geomagnetic effect on EAS, the observed data should be corrected for the side shower effect at all zenith angles.

The directional efficiency of the counter telescopes may not be so high as 90% as claimed by Shen & Singer (1969) and they may not be useful particularly to study the absolute zenithal distribution of showers. At the same time the directional efficiency of the system is not that bad as was implicitly meant by McCusker, et al., (1959) and Layson et al., (1960). Since our results, in view of the large asymmetries observed, indirectly indicate an efficiency of the order of 70% and even more. This contention was supported by the results of other workers too, as shown in the last chapter of this thesis. Therefore, it was felt that even if the directional efficiency is not very high, it is sufficiently high to suggest unambiguously, the existence of a significant influence of geomagnetic field on the density distribution of shower particles, at least qualitatively if not quantitatively. Any way this defect in the directional efficiency does not increase the observed geomagnetic effect but only dilutes it on the other hand. The true effect should be slightly higher than that observed by the telescopes.

Further, the main interest in conducting the experiment is not to determine the zenithal distribution of the shower frequency but only to observe the relative shower frequencies from the four main azimuths (East, West, South & North) at a particular zenith angle. When the telescopes were fixed at a particular zenith angle, and were directed in different azimuthal directions, the shower rates should be exactly the same from all the four main azimuths, ofcourse within the statistical errors, irrespective of the directional efficiency of the system, since exactly the same apparatus was used in all the directions, provided the circular symmetry of shower structure was to be true. The directional efficiency of the system cannot have any influence, in increasing the geomagnetic effect, whatsoever. But from the large asymmetries observed experimentally it is quite logical to believe that these asymmetries arise out of some physical reality i.e., the geomagnetic effect.

The efficiency of the counters does not remain constant with time and changes slightly, but this will not lead to any significant error.

Since fourfold coincidences were recorded the number of chance coincidences becomes almost insignificant. Even if they were taken into account, they only increase the observed geomagnetic effect by a fraction of a percent and hence can be neglected.

Another disadvantage is the uncertainity in calculating the energy of the shower initiating primaries for which the experimental set up responds. Only the order of magnitude can be estimated. This is even more complicated when the telescopes were inclined at various zenith angles. This will lead to some difficulty in determining the geomagnetic effect for showers of various sizes.

Even with some sort of core selector like a P - set it is very difficult to locate the actual position of the shower core, unless a very complicated and expensive piece of apparatus is used in conjunction with the P-set. The core may fall anywhere within 6-7 m of the set. This is all the more true in the case of G.M. Counter telescopes, and may introduce some error in the observed effect. Once again this uncertainty dilutes the observed effect rather than enhancing it.

In my experiment, searching for directional asymmetry, the apparatus should be directed in different directions at frequent and regular intervals, in rotation. This is recommended mainly to avoid the effects of time variations of the intensity, the statistical fluctuations and to a small extent, the effect of any slight variation in the accessories like electronic circuitary etc. For certain practical difficulties this was not done. However, it is well known that EAS have practically negligible time variation (only fraction of a percent) and can be safely neglected.

It is believed by some physicists that very big objects like huge buildings and mountains in the neighbourhood of the experimental arrangement may bounce off some of the particles and give rise to erroneous results, sometimes. This becomes particularly significant in the case of showers due to the very large number of particles associated with them. Unfortunately at Gulmarg there are high mountains all around the experimental site excepting in the north. It is extremely difficult to assess as to what extent the experimental results were influenced by those mountains, if at all they had any influence.

EAST-WEST ASYMMETRY.

Though the main aim of the investigation was to find out the geomagnetic effect on EAS, there is one more interesting point to note. At all zenith angles from 15°-60° for the three separations 10 m, 25 m and 40 m, the shower rate is slightly more from the west direction than from the East. The same is true with the experimental results of Chaloupka too, Table I. This East west asymmetry is shown in Table-VI. It can be seen that for 10 m separation the asymmetry gradually increases from 15° to 60° zenith angle. But for 25 m and 40 m, it reaches a maximum at 45° zenith angle and then comes down. This is just similar to the variation of East-West asymmetry observed for the hard component, for instance, by Gill & Khera (1957). Since the data are not corrected for pressure and temperature variations, it is not known whether this is just accidental coincidence or the East-West asymmetry does really exist for EAS. In case it really exists, it should be attributed mainly due to the mesonic component of the showers, in view of the considerable magnetic deflection of μ-mesons suggested by Oren(1959). Due to the large statistical errors and not very high directional efficiency of the telescopes no definite conclusions need be drawn. The experimental evidence available at present is not sufficient to suggest definitely the existence of this E-W asymmetry.

TABLE - VI

East - West percentage asymmetry of EAS.

Zenith angle Z	East - West asymmetry of extensive air showers.		
	10 m:	25 m:	40 m:
0°			
15°	2.61 ± 3.34	10.34 ± 4.32	7.95 ± 5.38
30°	7.61 ± 3.32	6.86 ± 3.82	9.30 ± 5.70
45°	9.01 ± 3.57	11.70 ± 4.45	10.71 ± 5.53
60°	13.03 ± 5.57	5.22 ± 4.31	5.55 ± 5.32

CONCLUSION

From the experimental results and discussion already given it is quite logical to conclude that at moderate latitudes and mountain altitudes the geomagnetic field has a considerable and well detectable influence on the density distribution of EAS. Qualitatively there is a fairly good agreement between the results of various authors. The percentage asymmetry between the shower rates from E-W and N-S increases not only with the separation between the two telescopes but also with the zenith angle at which the telescopes are inclined. Almost all the experiments conducted to investigate this geomagnetic effect indicate a very large effect when compared with the theoretically predicted value. This discrepancy between the theory and experiments remains to be explained.

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CHAPTER - IV.

GEOMAGNETIC EFFECT OF EXTENSIVE AIR SHOWERS NEAR SEA LEVEL.

ABSTRACT

Cocconi theoretically predicted a value of about 2% at sea level and 8% at mountain altitudes for the geomagnetic effect of EAS. Several authors while attempting to verify this prediction experimentally observed surprisingly much larger effect. The experimental observations were found to be not at all consistent with theory. Our results at Gulmarg also confirmed this view. To test the theoretical prediction for sea level it was thought worthwhile to run the experiment at Aligarh, (alt. 208 m; a.s.l) with an apparatus exactly similar to that used at Gulmarg. The sea-level data show a significant average effect of about 6% for 40 m separation between the telescopes. The results were in agreement with those of Oren at Haifa (alt; 180m) which show an average effect of 10-11%.

Oren experimentally observed an effect of (10±4)% for μ-mesons which was in conformity with his theoretical estimates. The geomagnetic effect seems to be quite sensitive to the altitude of the point of observation. It also appears that the geomagnetic effect of electronic component might be playing a dominant role at mountain altitudes.

INTRODUCTION

Extensive air showers are the manifestations of the collisions of ultra-energetic cosmic ray primaries in the atmosphere. They consist of mostly electrons and photons and to some extent protons, neutrons, π -mesons and μ -mesons. Cocconi (1954) made approximate calculations for the deflection of electrons in the earth's magnetic field and showed that the azimuthal shower structure should be modified, from circular symmetry to elliptical symmetry, with the major axis in the geomagnetic East-West direction. According to his calculations the ellipticity for vertically incident showers should be about 2% at sea level and about 8% at mountain altitudes, for latitudes below 50°. Several authors, Chaloupka (1954), Dubinsky-Chaloupka et al. (1956) and Nikolsky and Sotnevich (1956) experimentally verified this theoretical prediction and found surprisingly much larger effect than predicted by the theory. The results also indicate that the ellipticity increases with distance from the shower core. The same effect was investigated at Gulmarg, with two G.M. counter telescopes. The results, already presented in the preceding chapter, not only confirm the observations of the above mentioned authors, but also suggest that the ellipticity increases with the zenith angle at which the telescopes were inclined.

While attempting to explain the discrepancy between the theory and experiments, alternative possibilities were explore In this process, Oren (1959), following the calculations of

Khristiansen (1958) for the deflection of μ -mesons in the earth's magnetic field, roughly estimated the influence of the geomagnetic field on various components of EAS: a) primary particles; b) π -mesons; c) μ -mesons and d) their decay electrons. Although the calculations performed are only to estimate the order of magnitude for the geomagnetic effect, they enabled him to classify the relative role of the geomagnetic field on various components of EAS. His calculations show that of all the nonelectronic components - primaries, π -mesons and μ -mesons only μ -mesons seem to contribute to the ellipticity of shower structure, in an appreciable manner.

In view of the large discrepancies observed between the experimental results and the theory it is reasonable to suspect that the theoretical prediction might not be correct even at sea level. Moreover, from a comparison of the results of various workers, even after taking into account the latitude and altitude of the places at which the experiments have been conducted, it appears that the geomagnetic effect is quite sensitive to the altitude of the point of observation above sea level. With a view to test this conclusion, it was thought worthwhile to continue the investigation at Aligarh (alt. 208m) with an apparatus exactly similar to that used at Gulmarg (alt. 2710m). Even at Aligarh, the geomagnetic effect was significant, about 9%, for 40 m separation between the telescopes.

THEORETICAL ESTIMATES: (Christiansen (1958) & Oren(1959).

For the sake of continuity the theoretical estimates of Christiansen and Oren for the influence of geomagnetic field on various components of EAS are given below. EAS particles may diverge from the direction of flight of the primary particle initiating the whole shower due to the following reasons:

1) Angular divergence of secondary particles:
   a) in elementary acts of the nuclear cascade process, and
   b) in acts of spontaneous decay.
2) Coulomb scattering of charged particles by atomic nuclei of air.
3) Deflection of the charged shower particles in the earth's magnetic field.

After the discovery of the "anomalous" width of the shower by Zacepin and Miller, (1947), it was supposed by Dobrotin & Zacepin (1953) that the angular divergence of secondary particles is the main phenomenon responsible for the broad spatial divergence of shower particles. However, a more detailed analysis of the second and third points by Khristiansen shows that this conclusion must be reconsidered, since the earth's magnetic field plays a significant role in the divergence of electrons and μ-mesons around the shower axis. His calculations particularly show that the spatial divergence of μ-mesons can be due to principally the coulomb scattering and their deflection in the earth's magnetic field. He claimed that his calculations were in agreement with the experimental results of Skvarelidze (1956). In fact Oren only extended the calculations of Khristiansen to the shower primaries and π - mesons.

<u>Deflection of primary particles:-</u>

The radius of curvature of a relativistic charged particle of energy E in the magnetic field is

$$\rho_{(cm)} = \frac{E\,(ev)}{300\,B\,(gauss)} \qquad \ldots (1)$$

Thus the shower axis, being the direction of motion of the primary particle, will be inclined to the zenith by an angle θ, given by:

$$\theta_{(rad)} = \int_{\infty}^{R} d\theta = \int_{\infty}^{R} \frac{dr}{\rho} = \frac{300\,M}{2ER^2} = \frac{2.88 \times 10^{10}}{E\,(ev)} \qquad \ldots (2)$$

where M= 8.1 x 10^{25} gauss cm^3, dipole moment of the earth, and R= 6.4 x 10^8 cm, radius of the earth.

For a particle of 10^{14} ev, $\theta \approx 3 \times 10^{-4}$ radian. The shower axis, being inclined to the zenith by an angle θ, will cause lines of equal density to be ellipses, with the major axis in the geomagnetic E-W direction. The ratio of the axes will be cos θ, for small angles:

$$\cos\theta = 1 - \frac{\theta^2}{2} = 1 - \frac{3.76 \times 10^{20}}{E^2\,(ev)} \qquad \ldots (3)$$

The effect caused by the deflection of the primary particle will be of the order 10^{-7} even for an energy as low as 10^{14} ev and so it can be neglected in the energy region of the shower primaries.

Deflection of π-mesons:-

π-mesons of energy E (ev) coming from the zenith and after travelling a distance (h) will make an angle (θ) with the vertical direction given by:

$$\theta = \frac{h}{\rho} = \frac{300\,B\,h}{E} = \frac{6\times10^{6}\,h_{(km)}}{E\,(ev)} \qquad \ldots (4)$$

where B=0.2 gauss, the horizontal component of the geomagnetic field. Only those pions whose m.f.p. for decay is large compared with (h) should be taken into consideration.

Thus one gets $l_{(km)} = \frac{c\,\tau_0\,E}{M_\pi c^2} = 5\cdot6\times10^{-11}E_{(ev)} \ldots (5)$

This dispersion due to the geomagnetic field should be compared with the dispersion of the pions at production. The pions are contained in a cone of half angle given by:

$$tg\ \bar{\theta}_{\frac{1}{2}} = \sqrt{2/\gamma_L} \qquad \ldots (6)$$

where γ_L is the energy of the primary in Bev.

Oren calculated the angles of deflection of pions in the geomagnetic field as a function of their energies and found that the angle of deflection in the geomagnetic field is always smaller by one or two orders of magnitude than the dispersion at production and hence the contribution of pions to the geomagnetic effect can be neglected.

Deflection of μ-mesons:-

In EAS μ-mesons are produced by the decay of $\pi^{\pm}$ and $K^{\pm}$ mesons in the upper layers of the atmosphere. According to the experimental data of Rossi et al., (1953) the generation of μ-mesons mostly takes place in the altitude range of 5-20 km above sea level. μ-mesons will interact very weakly with nuclei. They do neither undergo radiation losses comparable to those of electrons, nor do they undergo nuclear collisions as do protons or neutrons and consequently they cover a large distance from the point of generation to the point of observation. Because of the large path length for μ-mesons in the geomagnetic field an essential role is played in the lateral divergence of μ-mesons both by their coulomb scattering on nuclei of air atoms and by their deflection in the earth's magnetic field, even in the case of relatively large value of energy. The lateral distribution of electrons and μ-mesons was investigated by several authors. According to the experimental data of Antonov et al., (1967), and Ejdus et al., (1962) On the lateral distribution of low energy μ-mesons, the lateral distribution function of μ-mesons falls off much more slowly than the electron flux density even at great distances of the order of hundreds of meters from the shower axis and behaves as $1/r$.

According to Khristiansen the mean square deflection, taking the ionization loss into consideration is

$$\overline{\gamma_s^2} = \int_0^H \frac{h^2 E_s^2 t_o \alpha e^{-\alpha h}}{\left[E + E_c t_o (1 - e^{-\alpha h})\right]^2} dh \qquad \ldots (7)$$

where H= the height of generation of μ-mesons above the observation level.

t_o= the depth of observation point in radiation lengths.

E_s= 21 Mev, parameter of multiple scattering,

α = $(\frac{1}{7000})$ m^{-1}, coefficient of the barometric equation,

E_c= 84 Mev, critical energy in air.

The deflection of μ-mesons in the geomagnetic field is given by

$$\gamma_{mag} = \int_0^H \frac{h\, dh}{\rho} \quad \text{where } \rho = \frac{E + E_c t_o (1 - e^{-\alpha h}) \times 10^5}{3 B} \qquad \ldots (8)$$

(E &E_c in Bev and B in gauss).

For the evaluation of the geomagnetic effect it is necessary to find out the ratio $\gamma_{mag} / \sqrt{\overline{\gamma_s^2}}$. With an accuracy of at least 10%, this ratio is equal to;

$$\frac{\gamma_{mag}}{\sqrt{\overline{\gamma_s^2}}} = \frac{0.218 \times (\alpha H)^2}{\sqrt{2 - e^{-\alpha h}\left[1 + (1 + \alpha H)^2\right]}} \qquad \ldots (9)$$

Using the expressions 7, 8 & 9, Khristiansen calculated the values of $\sqrt{\overline{\gamma_s^2}}$ and γ mag as shown in Table -I, assuming the altitude

TABLE - I.

Geomagnetic effect of μ-mesons in EAS: Khristiansen(1958).

$\sqrt{\overline{\gamma_s^2}}$ Experimental.	$\sqrt{\overline{\gamma_s^2}}$	r_{mag}	$\frac{\gamma_{mag}}{\sqrt{\overline{\gamma_s^2}}}$	$\sqrt{1+\frac{\gamma_{mag}^2}{\overline{\gamma_s^2}}}$
400m.	300m.	200m.	0.67	1.203

of generation of μ-mesons H=10 km above sea level, and considering that the energy of μ-mesons at great distances from the shower axis is close to the minimum energy still registered by the detector and equal to 3×10^8 ev in the experiments of Antonov et al; Ej dus et al. and Abrosimov et al., already referred to, for sea level. He also showed the experimental value of $\sqrt{\overline{\gamma_s^2}}$ at sea level.

From Table-I it is clear that an essential role is played by both the coulomb scattering as well as the deflection in the earth's magnetic field, in the lateral distribution of low energy μ-mesons, which are usually studied in the experiments. To evaluate the true divergence of μ-mesons, the deflections due to the angles between μ-mesons and π-mesons, and the primaries also should be taken into account. However, the relative role of all these factors cannot at present be determined definitely without additional experimental data, and, above all, data on the lateral distribution of mesons, their energy spectrum and also the actual altitude of their generation in the atmosphere.

Next it is worthwhile to consider the sensitivity of $\sqrt{\overline{\gamma_s^2}}$ and γ_{mag} to the altitude of generation of μ-mesons. The value of γ_{mag} is highly sensitive to H. According to equation (8) and with account taken of ionization losses, $\gamma_{mag} \sim H^2$. The value of $\overline{\gamma_s^2}$ is somewhat much less sensitive to H. Oren actually calculated the ratios of $\frac{\gamma_{mag}}{\sqrt{\overline{\gamma_s^2}}}$ as a function of H, which are shown in Table-II.

TABLE - II.

Ratios of $\gamma_{mag}/\sqrt{\overline{\gamma_s^2}}$ as a function of production height of μ-mesons, H. (Oren (1959) :-

H (Km)	$\frac{\gamma_{mag}}{\sqrt{\overline{\gamma_s^2}}}$	$\sqrt{1+\frac{\gamma_{mag}^2}{\overline{\gamma_s^2}}} = 1$
1	0.138	0.002
2	0.207	0.021
3	0.286	0.035
4	0.331	0.050
5	0.376	0.068
6	0.431	0.089
7	0.486	0.112
8	0.543	0.138
9	0.606	0.169
10	0.684	0.220

Deflection for decay electrons:-

Because of the considerable deflection of the μ-mesons it is reasonable to suspect that secondary cascades, started by decay electrons of the μ-mesons will contribute to the geomagnetic effect. But actual calculations show insignificant contribution of the decay electrons to the geomagnetic effect.

Deflection for electrons of electromagnetic cascade:-

These calculations due to Cocconi were already given in the previous chapter.

RESULTS AND DISCUSSION:

The present investigation of the geomagnetic effect on EAS at Aligarh (alt: 208m) was only a continuation of the study made at Gulmarg (alt: 2710m). This was taken up to determine the effects of altitude variation on the geomagnetic effect of EAS. The experimental arrangement was just similar to that used at Gulmarg, consisting of two G.M. Counter telescopes of semiangle 10° each. All other details of the experiment were exactly the same as described in Chapter II. The separation between the telescopes was 40 m. Fourfold coincidence rates from West and North were recorded for three positions of the telescopes i.e., vertical, 45° zenith angle and horizontal. The position of the telescopes was changed from west to north and vice versa roughly every 20 days. The zenith angle of the telescopes was also changed at regular intervals in rotation. The pressure and temperature variations were also recorded simultaneously. The data were collected during the period November 1960 to May 1961, with some unavoidable interruptions now and then.

The intensity variations of EAS are to a great extent due to causes other than the intensity variations of the primary radiation i.e., to changes in the atmospheric conditions. The actual knowledge of shower intensity variations arising from atmospheric causes is therefore an indispensable first step in any further investigation and inference from results obtained. This becomes even more important when the effect being looked for is very small.

Among the atmospheric effects on EAS, the pressure coefficient has been known for quite sometime and which has been investigated most. An increase in the pressure effectively corresponds to the apparatus being situated at a greater depth, and hence the shower rate of a given size decreases, and vice versa. The experimental results of several authors with apparatus of different sizes and base lengths showed that the barometric coefficient of EAS in the lower atmosphere (below 650 gm/cm) is approximately constant and equal to about - 10% per cm. Hg. However, most recent work, Cranshaw et al.(1958) suggests that the barometric coefficient of showers increases with the shower size for showers containing more than 10^7 and is significantly greater than - 10% cm^{-1} Hg. In this case only β = -10% cm^{-1} Hg was used to correct the data since the energy of the showers recorded is not very high.

Another atmospheric effect on EAS is the temperature effect. A change in temperature T above the shower detecting apparatus is reflected by a change in the lateral spread of the shower and hence in the efficiency of detection of a fixed arrangement of counters. Hodson (1951) measured a seasonal variation for showers, which , when corrected for barometric effects, gave a temperature coefficient of $\theta = -(0.38 \pm 0.11)\%$ per ^{o}C. The height at which the temperature is measured will affect the magnitude of the temperature coefficient. Hodson assumed that the most meaningful height at which to correlate shower rate with temperature is one cascade unit above the detecting apparatus since most of the lateral spread of showers takes place within first cascade unit above the apparatus. But this assumption does not seem to be compatible with the observations of Citron and Stiller (1958). These authors found that partial correlation coefficients with respect to temperature vary little with the level at which the temp. is taken, only as long as one of the levels between 850 mb and 300 mb. is chosen. It was suggested that the most ideal method would be to take the average temperature over all the levels from 850 mb to 300 mb. As the upper air temperature data was not available, only the base level temperature variations were used in applying the temperature correction.to our data. This may introduce some error in the results.

The experimental results are given in Tables III, IV & V. The errors shown are standard deviations. In Table IV the percentage asymmetries are calculated without applying pressure and temperature corrections to the data using the equation $I = I_0 - (\beta \cdot \Delta P + \theta \cdot \Delta T)$. In Table V, the percentage asymmetrics are calculated after correcting the data for pressure and temperature variations. The calculated percentage asymmetries (7.8%, 2.2% and 8.7% at 0^o, 45^o and 90^o respectively) are not much different before and after applying the pressure and temperature corrections. The final results (Table V) give an average asymmetry of about 6%. These results are compared with those at Gulmarg, corresponding to 40 m separation between the telescopes in Fig. 10. The upper curve corresponds to Gulmarg (alt. 2710m) data and the lower curve to that at Aligarh (alt. 205 m). The lower curve is somewhat flat whereas the upper one shows a steep rise with zenith angle. However this is not observed at Gulmarg for any of the three separations 10 m, 25m and 40m. The lower curve also shows a broad depression at 45^o zenith angle. It is somewhat difficult to assign any reason for this depression. Probably this might be due to the absence of the contribution of electronic component to the geomagnetic effect at such large zenith angles. This in turn is due to the very large increase in the coulomb scattering of electrons at larger zenith angles because of their low energies at sea level. However, an effective explanation cannot be given to this decrease in the geomagnetic effect at 45^o zenith angle without having a definite idea of the relative role of the geomagnetic effect from the electronic and μ-mesonic components in EAS.

TABLE - III.

Coincidence rate per hour from West and North for 40m seperation between the telescopes at Aligarh (alt. 205m).

Zenith angle 'Z'	Total number of counts. M	Total time in hours. T	Average coinci-dence rate per hour. N = M/T.	Average coin-cidence rate per hour with standard devi-ation. N ± σ
		WEST.		
0°	2054	395	5.20	5.20 ± 0.08
45°	1739	472	3.69	3.69 ± 0.07
90°	707	297	2.38	2.38 ± 0.06
		NORTH.		
0°	2026	424	4.78	4.78 ± 0.07
45°	1624	440	3.69	3.69 ± 0.06
90°	651	302	2.16	2.16 ± 0.06

TABLE - IV.

Percentage asymmetry at Aligarh (alt. 205m) for 40m separation between telescopes: data not corrected for press and temp. variations.

Zenith angle 'Z'	Average coincidence rate per hour from the West. $N_w \pm \sigma w$	Average coincidence rate per hour from the North. $N_n \pm \sigma n$	Percentage asymmetry $\frac{2(N_w-N_n)}{(N_w+N_n)} \times 100\%$
0°	5.20 ± 0.08	4.78 ± 0.07	8.43 ± 0.02
45°	3.69 ± 0.07	3.69 ± 0.06	.....
90°	2.38 ± 0.06	2.16 ± 0.06	9.69 ± 0.03

TABLE - V.

Percentage asymmetry at Aligarh (Alt. 205m) for 40m seperation between telescopes; data corrected for press and temp. variations.

Zenith angle 'Z'	Average coincidence rate per hour from the West. $N_w \pm \sigma_w$	Average coincidence rate per hour from the North $N_n \pm \sigma_n$	Percentage asymmetry $F = \frac{2(N_w - N_n)}{(N_w + N_n)} \times 100\%$
0°	5.17 ± 0.08	4.78 ± 0.07	7.83 ± 0.02
45°	3.73 ± 0.07	3.65 ± 0.06	2.18 ± 0.02
90°	2.40 ± 0.06	2.20 ± 0.05	8.70 ± 0.03

The observed geomagnetic effect (lower curve) is slightly higher with the telescopes horizontal than in the vertical position (7.8% at 0° and 8.7% at 90°). After all this is understandable. Because of the $I \propto \cos^{8}\theta$ relation for the zenithal distribution of EAS at sea level, practically no showers come from angles greater than 60°. The shower rate recorded by the apparatus with the telescopes horizontal is mostly due to the background from the vertical and near vertical directions. In the horizontal position the apparatus selects showers of higher density when compared to the vertical position. In effect this corresponds to a larger separation between the telescopes and hence the increase in the observed geomagnetic effect, in the horizontal position. From the graph the highly sensitive nature of the geomagnetic effect with the altitude of observation is quite obvious. The shape of the lower curve suggests that near sea level the geomagnetic effect is significant for only vertically incident showers.

Further it is interesting to compare our results at Aligarh (alt. 206 m) with those of Oren (Haifa, alt: 180 m) though the experimental arrangements were not exactly similar. Oren's theoretical estimates showed that the contribution to the geomagnetic effect of the primary is negligible, the contribution of pions is not more than a faction of a percent and only the contribution of μ -mesons is significant. With a view to test his theoretical estimates, Oren measured the ratio of particle densities at 7 m and 14 m from the shower core and the ratio of μ -meson densities at 14 m distance with a shielded tray in a hodoscope experiment. Within the statistical uncertainity no significant difference in the geomagnetic effect was observed for the two separations 7 m and 14 m but the results even after correction for the distribution of core locations indicate an average effect of (11.5 ± 6.5)%. For μ-mesons registered at 14 m, the asymmetry was (10 ± 4)%. Although the statistical errors were so large not to prove conclusively the importance of μ-meson contribution to the geomagnetic effect, the results clearly suggest it. His results indicate that only μ-mesons contribute mostly to the geomagnetic effect at sea level. Our experimental results at Aligarh, even for 40m separation show only an average effect of 6% whereas those of Oren give an average of (11.5 ± 5.5)% for 7 and 14 m. In fact our results should have given a large effect than this. However there are two reasons for this discrepancy; a) large statistical errors in Oren's experiment, and b) large uncertainities in the location of shower core with G.M. counter telescopes, which dilutes the observed geomagnetic effect. Nevertheless, the results agree qualitatively.

Oren connected the increase in the ellipticity with the distance of the detectors from the shower core with the relatively flat lateral distribution of μ-mesons and their appreciable ellipticity. But it is doubtful whether this reason alone can account for all the increase in the ellipticity with distance.* Either at sea level or at mountain altitudes,

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* Dubinsky-Chaloupka et al., observed no geomagnetic effect at 15.5 m from the shower core, but they found 40% effect at 30m and 60% effect at 50m. Our own results of Gulmerg experiment are given in Table-V Chapter III, also support this view.

the lateral distribution function of μ-mesons ($1/r$) is smooth and flat, even at large distances of the order of several hundreds of meters from the core. Hence the geomagnetic effect of μ-mesons alone cannot explain the increase in the ellipticity with distance from the core. A little consideration will show that the electronic component must be playing a dominant role at mountain altitudes, though not at sea level. He also concluded that his results do not agree with those of Chaloupka, Dubinsky-Chaloupka et al. Any way the discrepancy is not serious when the altitude difference of the places and the separations of the detectors are taken into account. But in view of the large statistical errors involved in these three experiments a quantitative comparison is not of much help.

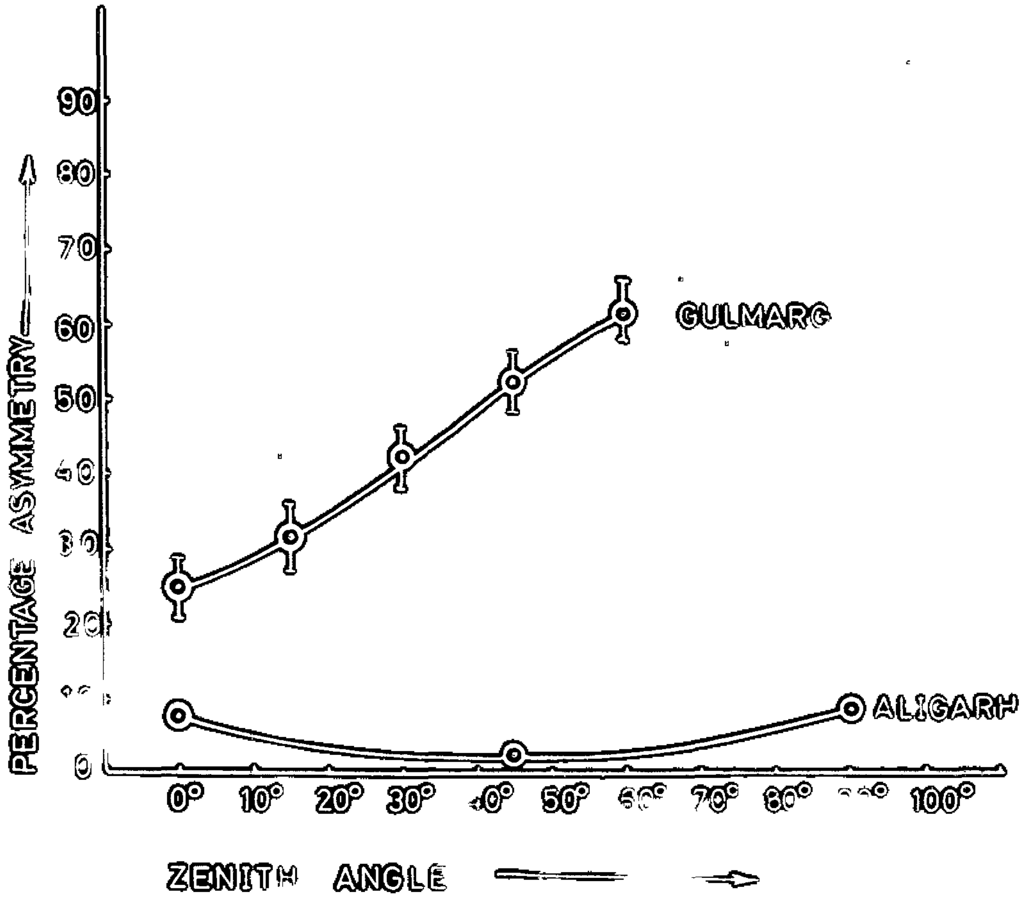

FIG.9 COMPARISON OF PERCENTAGE ASYMMETERIES AT ALIGAR (alt.205m) AND GULMARG (alt.2710 m).

CONCLUSION

From the experimental results and discussion presented above it can be reasonably concluded that even at sea level at considerable distances from the shower core (of the order of 20m) the observed geomagnetic effect is significant and much higher (3 or 4 times) than the theoretically predicted value of about 2%. Our results at Aligarh give an average asymmetry of about 6% and those of Oren at Haifa give 10-11%. Besides, experimental results of Oren suggest that near sea level most of the observed geomagnetic effect can be attributed only to μ-mesons. A comparison of our experimental results at Aligarh and Gulmarg (Fig. 1) clearly points out the sensitive nature of the geomagnetic effect with altitude of the point of observation above sea level. It appears that although the μ-mesonic component plays a very important role in its contribution to the geomagnetic effect near sea level, electronic component might be playing an equally significant role, or even a dominant role at higher altitudes. It will be really worthwhile to determine the relative contribution of mesons and electrons to the geomagnetic effect near sea level as well as at higher altitudes, in the future investigations. However, additional data on the lateral distribution and energy spectrum s for μ-mesons and electrons of EAS, and the Precise knowledge of the altitude of generation of μ-mesons is also essential, for any helpful quantitative comparison between the theory and experiments.

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CHAPTER- V.

DIRECTIONAL PROPERTIES OF EXTENSIVE AIR SHOWER ARRAYS.

ABSTRACT

In order to arrive at the true value for the geomagnetic effect on EAS, the experimental data presented in chapters III & IV should also be corrected for the defect in the directional efficiency of the telescopes. But, due to the lack of reliable experimental data, this could not be done. However, some interesting observations were made regarding the directional efficiency of EAS arrays.

The simple extensive air shower array proposed by Shen & Singer for which they claimed about 90% directional efficiency, has been tested by two groups of physicists, McCusker et al., and Leyson et al., using it in conjunction with cloud chambers and scintillation counters, respectively. They concluded that the proposed set up has got very poor efficiency in selecting showers in preferred directions. However, there are some significant differences between the results of various authors, on this problem. It is possible to make further improvements in the performance of the device, besides the two methods suggested by Mc Cusker et al.

INTRODUCTION

The experimental arrangement consisting of two G.M. counter telescopes used in the study of geomagnetic effect on EAS at Gulmarg and Aligarh has got certain weaknesses. It is not an ideal one for the proposed study mainly due to the not very high directional efficiency of the telescopes to detect showers in a preferred direction. They are susceptible, to some extent, to be triggered by shower particles coming from angles other than the defined aperture of the telescopes. To get a true value of the geomagnetic effect on EAS the data should also be corrected for this defect in the directional efficiency. There were large discrepancies between the results of various workers. It was felt extremely difficult to assign any particular value (quantitatively) for the directional efficiency of the telescopes and hence the correction could not be applied. Any way this defect only dilutes the observed geomagnetic effect rather than enhancing. The geomagnetic effect only increases by applying this correction. Therefore, this correction need not be a serious objection to the conclusions drawn regarding the geomagnetic effect of EAS in chapters III & IV.

Shen & Singer (1967) proposed a simple extensive air shower array consisting of three G.M. counter telescopes, placed at the vertices of a triangle for which they claimed a directional efficiency of 90%. This arrangement has been tested by Mc Cusker et al., (1959) using a similar unit in conjunction with two cloud chambers. From their experimental results they concluded that there is no great improvement in the angular resolution of the apparatus suggested by Shen & Singer, and it is not of much value in looking for anisotropy in the high-energy primary cosmic radiation. Their results indicate that the vertical arrangement leads only to 7% (or at the best 14%) enrichment of showers coming from the near vertical direction. But our results, Bhaskara Rao & Gill (1960), obtained during the course of the investigation on the influence of geomagnetic field on EAS at Gulmarg, suggested an enrichment value of the order of 55%. With a view to check our Gulmarg data, a similar experiment was conducted at Aligarh (alt: 205m), again with two telescopes. The experimental results confirm our previous conclusion giving an enrichment figure of 54% which is very high when compared to that of Mc Cusker, et al. Moreover, Mc Cusker, et al., contented that there is no serious disagreement between their own results and those of Shen & Singer. Even this contention is not justifiable as shown at a later stage. Further, their results are in disagreement not only with our results, but also with those of Shen & Singer and Rathgeber (1959). Although the experimental results of Layson, et al., (1960) agree well with their theoretical calculations, their shower data do not seem to follow the well established $\cos^n\theta$ law. Finally, whatever might be the actual directional efficiency and usefulness of the shower array proposed by Shen & Singer, the observed discrepancies are very significant and worth consideration. Further slight improvement can be made in the device.

RESULTS AND DISCUSSION:

Here four instances are given, including our own results at Aligarh, to point out the large discrepancies between the results of various authors.

A

The arrangement used consisted of two G.M. counter telescopes of semiangle 10^0 each. All other details of the experiment were the same as described in Chapter - II. The separation between the telescopes was 40 m. Fourfold coincidences were recorded from West and North, the telescopes being fixed at different zenith angles in rotation. The position of the telescopes was changed from West to North and vice versa roughly for every 20 days. The experimental results were shown in Table-I, after applying the pressure and temperature corrections. From the Table it can be seen:

TABLE I

Coincidence rate vs. zenith angle for 40 m separation between the telescopes at Aligarh.

Zenith angle 'Z'	Coincidence rate per hour from West	Coincidence rate per hour from North	Average coincidence rate per hour
	$N_w \pm \sigma_w$	$N_n \pm \sigma_n$	$N \pm \sigma$
0°	5.17 ± 0.08	4.78 ± 0.08	4.98 ± 0.08
45°	3.73 ± 0.07	3.65 ± 0.06	3.69 ± 0.07
90°	2.40 ± 0.06	2.20 ± 0.05	2.30 ± 0.06

$$\text{percentage enrichment} = \frac{V - H}{V} \times 100\% = 86\%$$

Where V = coincidence rate with the telescopes in the vertical position, and

H = coincidence rate in the horizontal position.

Here it should be remembered that the experimental results of McCusker et al., actually give only 7% enrichment which is very low when compared to our value of 86%.

B

Some of the experimental results of Rathgeber were given in Table II. From the columns (x) and (y) enrichment values can be calculated as 86% and 81% respectively. Evidently there is large difference between the enrichment values of McCusker, et al., and Rathgeber.

C

Experimental results of Shen & Singer and McCusker, et al., were compared in Table - III. The experimental set up used by McCusker, et al., was just similar to that of Shen & Singer. Shen & Singer's results show a difference of 86% in the counting rate for a difference of 13.2° in the effective zenith angle, whereas those of McCusker, et al., show only a variation of 16% for 19.2° difference of effective zenith angle. In fact McCusker, et al., should have observed a

TABLE- II

Shower rate in counts per hour

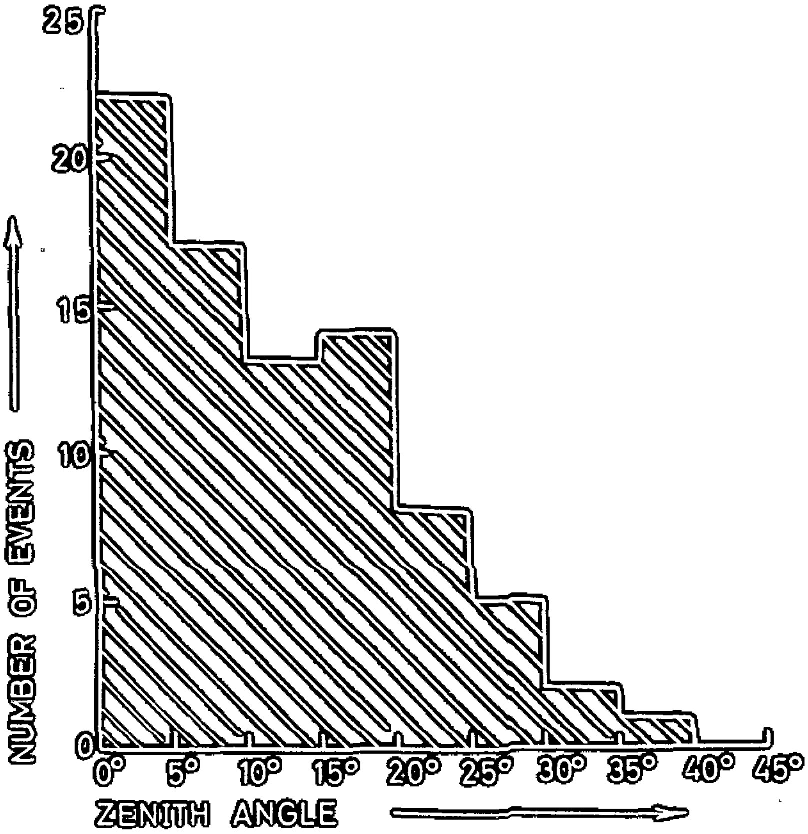
From Rathgeber(1959).

Zenith angle 'Z'	Counters in each telescope	
	(X) 2 counters	(Y) 3 counters
0°	1.96 ± 0.29	1.56 ± 0.27
90°	1.25 ± 0.23	0.77 ± 0.16

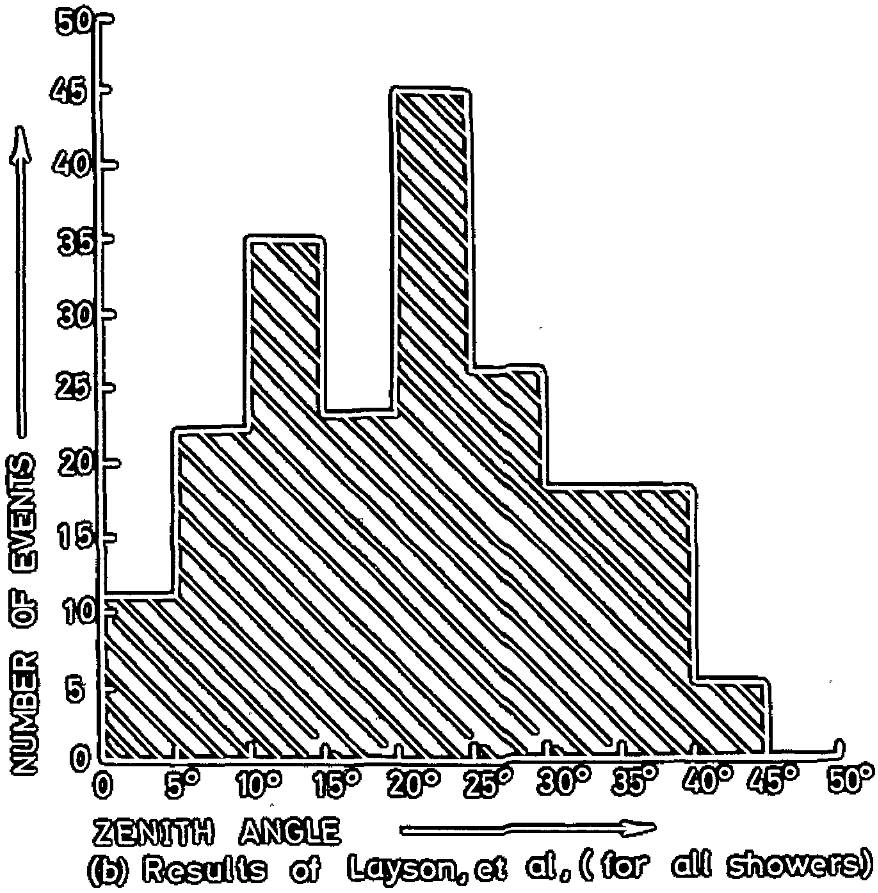
TABLE- III

Experimental determination of zenith angle distribution.
From Shen & Singer (1957) and McCusker, et al., (1959).

Separation between the extreme counters in Cms.	Effective zenith angle	Difference of effective zenith angle	Sixfold coincidence rate per hour	Percentage difference in the coincidence rate.
		Shen & Singer.		
(i) 46.2	6.3°	13.2°	0.30 ±0.020	53%
(ii) 14.8	19.5°		0.46 ±0.028	
		McCusker, et al.,		
(i) 67.0	5.6°	19.2°	0.605 ±0.039	14%
(ii) 16.0	24.8°		0.692 ±0.029	



(a) Resultsof Mc Cusker, et al.



(b) Results of Layson, et al, (for all showers)

FIG.10 THE FREQUENCY OF SHOWERS OF DIFFERENT ZENITH ANGLES SETTING OFF THE ARRANGEMENT difference larger than 58%. Moreover, McCusker, et al., contented that their experimental results are not in serious disagreement with those reported by Shen & Singer. From the above table it is easy to see how they are not justified in their contention.

D

The directional response of the same set up was also tested by Layson, et al., using it in conjunction with the Sydney air shower apparatus. Although they claim that their experimental results are in good agreement with their theoretical calculations, their data do not seem to follow the well known $\cos^n\theta$ law (n = 8 at sea level). The zenithal distribution of showers given by them in the form of a histogram (corresponding to all showers) is compared with the distribution obtained by McCusker, et al., with the help of cloud chambers, (Fig-10). Even if the directional efficiency of the system were to be low, the observed data should have followed the $\cos^n\theta$ law. Data obtained by McCusker, et al., follows the theoretical distribution at least qualitatively, whereas the histogram given by Layson, et al., is much different from what it ought to be. From Fig. (10-b) it can be seen that the telescopic system records more showers at larger zenith angles (from 5°-40°, at an interval of 5° each) than from the vertical and near vertical i.e., 0 - 5°. In particular the shower rate between 20-25° is four times the rate at 0-8°. This discrepancy is of very serious nature, which requires some explanation. Rossi (1960) attributed the flat zenithal distribution of showers observed at Alto (alt: 4100m, shower size $10^7 < N < 3\times10^7$) to the fact that the showers are still near their maximum development at such high altitude for very high energy showers. But the same arguments cannot hold good in the case of shower sizes recorded at Sydney.

In view of the significant discrepancies in the experimental results of Mc-Cusker, et al., and other workers, and the irregularities of basic value in the zenithal distribution of showers recorded by Leyson, et al., one should be very cautious in drawing a quantitative conclusion regarding the directional efficiency of EAS arrays. It is to be emphasized that the directional efficiency of an array decreases at larger zenith angles because of the nonuniformity of the sideshower background. Since the zenithal distribution of showers is given by $\mathrm{Cos}^n\theta$, the shower rate decreases at larger zenith angles very rapidly. The relative proportion of the background showers increases with zenith and hence the directional efficiency decreases.

Mc-Cusker, et al, suggested two methods to improve the performance of the device: a) to use a tray of counters in anticoincidence with the telescopes, b) to encase the telescopes at both sides and ends in lead walls thicker than

20 cms. The second method has got the advantage of not rejecting high density showers arriving from near vertical direction. This can be still improved by using sets of two or more counters connected in parallel in the telescopes, instead of single counters, however at the same time keeping the aperture of the telescopes constant by adjusting the separation between the upper and lower sets suitably. This offers larger sensitive area for shower particles coming within the defined aperture of the telescopes and helps in reducing the percentage background of side showers from zenith angles other than the defined aperture in which we are not interested. This background can also be reduced by increasing the multiplicity of coincidence from six to nine, with a third set of counters in between the upper and lower sets of each telescope. These modifications do not have any significant effect on shower particles falling within the defined angle but considerably reduce the background.

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Reprinted from the Indian Journal of Physics Vol. XXXIV, No, 4, April 1960 pp. 153—158.

17

INFLUENCE OF GEOMAGNETIC FIELD ON EXTENSIVE AIR SHOWERS OF COSMIC RADIATION

A. BHASKARA RAO AND P. S. GILL

DEPARTMENT OF PHYSICS, MUSLIM UNIVERSITY, ALIGARH

(*Received, February* 10, 1960)

ABSTRACT. G. Cocconi (1954) pointed out that the deflection of air shower particles in the earth's magnetic field should produce some ellipticity of shower structure, and hence the lateral distribution of electrons around the shower axis should not be circular, but elliptical, with the major axis in the East-West direction. This effect was investigated at Gulmarg (alt. 2710 m: 24°–36′ N-geomagnetic lat.;) with two G.M. counter telescopes, for three separations 10 m, 25 m, and 40 m. The results show that there is a significant difference between the shower rates from East-West and North-South directions. This asymmetry in the shower rates is found to increase with the separation, and the zenith angle of the telescopes.

INTRODUCTION

G. Cocconi (1954) pointed out that D_m, the displacement of air shower particles due to the earth's magnetic field is not negligible in comparison with D_s, the projected lateral displacement due to multiple coulomb scattering, and this effect might be large enough to be detected as an asymmetry in the lateral distribution of electrons in air showers. It means the electrons are distributed elliptically, around the shower axis.

It has been evaluated in the first approximation, that the ratio of the two displacements is given by

$$D_m/D_s = 0.22 \cos \lambda/P.$$

Where λ is geomagnetic latitude, and
P is air pressure in atmospheres.

The combined displacement is $D_{m+S} = \left[D_m{}^2 + D_S{}^2\right]^{\frac{1}{2}}$; so that

$$D_{m+S} = D_S \left[1+ \left(\frac{0.22 \cos \lambda}{P}\right)^2\right]^{\frac{1}{2}}$$

$$\simeq D_S \left[1+ \frac{0.024 \cos^2 \lambda}{P^2}\right]$$

P. Chaloupka (July, 1954) measured this effect on the top of "Lommicky' Stit" (alt. 2634 m : 48° N. geomagnetic latitude) with two G. M. counter telescopes. The separation of the telescopes was 7 m. The telescopes were inclined at 45° zenith angle and successively directed towards East, West, South, and North. Fourfold coincidences were taken. He reported nearly 20% more showers arriving from the E-W direction than from N-S direction. Due to large statistical errors he did not draw any conclusion. Later Dubinsky, Chaloupka, *et al.* (1956) continued the investigation (alt. 1778 m: 48°*N*. geomagnetic lat.) in which they fixed up the position of the shower core, and measured the particle densities to the West and South of the core, at three distauces 15.5 m, 30 m, and 50 m. Though they did not find any variation for 15.5 m, they observed 40% and 60% greater densities in the West direction than in the South for 30 m, and 50 m distances respectively. Even in this case the statistical errors were large. The present investigation was carried out at Gulmarg (alt. 2710 m : 24°-36′ N. geomagnetic lat.) with improved statistics.

EXPERIMENTAL

The experimental arrangement was similar to that of Chaloupka, and the block diagram is shown in Fig. 1. It consisted of two G. M. counter telescopes T_1, T_2, with two trays in each. In each tray there were four counters (size 52 × 584 mm) filled with Argon and petroleum-ether. The separation of the counter trays in the telescopes was 950 mm. The pulses from the trays were carried to the cathode-follower and from there to the coincidence circuit, through a low impedance coaxial cable, type *KD*-49. Only fourfold coincidences were recorded by the recording unit. The counter trays were mounted on an aluminium frame, which was fixed to a wooden stand in such a way that the telescope can be fixed at any particular zenith angle.

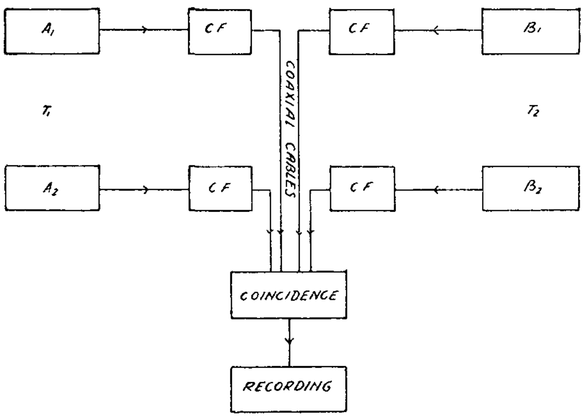

Fig. 1.

The asymmetry in the rate of showers was measured for three distances 10 m, 25 m, and 40 m between the telescopes. The telescopes were directed towards East, West, South, and North at zenith angles 0°, 15°, 30°, 45°, and 60°

and fourfold coincidences were recorded. Counters with a minimum plateau of 200 V were used in the experiment, and they were tested every day before starting the apparatus.

RESULTS AND DISCUSSION

The results of the experiment are given in Tables I, II, and III, for the three separations 10 m, 25 m, and 40 m. In any direction if the total number of counts recorded is M, during the total time T hours, then the shower rate in that direction is M/T per hour. The error in the shower rate is taken as $M^{\frac{1}{2}}/T$

The first table represents the shower rates from East, West, South, and North directions with the corresponding errors. In Table II the average shower rate from East-West directions is taken as x and the average shower rate from North-South directions as y. Next, the ratio x/y is calculated for the three separations and all the zenith angles as shown. If the circular symmetry of electrons around the shower axis is to be correct, the ratio x/y should be unity. But it can be seen that in all the cases, without exception, the ratio is larger than unity and far beyond the statistical errors. This clearly indicates that electrons in extensive air

TABLE I

Counting rates of showers from East, West, South, and North directions with corresponding errors

	Zenith angle Z	Showers per hour from the East $N_e \pm \Sigma_e$	Showers per hour from the West $N_\omega \pm \Sigma_\omega$	Showers per hour from the South $N_s \pm \Sigma_s$	Showers per hour from the North $N_n \pm \Sigma_n$
	0°	94.4±2.5	———	87.0±2.3	———
	15°	79.4±1.9	81.5±1.9	72.1±1.7	72.1±1.7
10 m	30°	69.5±1.5	75.0±1.9	63.0±1.5	61.2±1.5
	45°	60.4±1.5	66.1±1.7	52.9±1.3	53.8±1.3
	60°	50.9±1.3	58.0±1.5	45.6±1.2	47.4±1.2
	0°	58.9±1.9	———	52.5±1.6	———
	15°	49.5±1.5	54.9±1.7	40.0±1.3	40.6±1.2
25 m	30°	45.0±1.0	48.2±1.5	33.2±1.0	33.3±1.0
	45°	40.2±1.2	45.2±1.5	28.2±0.9	28.7±0.9
	60°	35.0±1.0	37.1±1.2	22.4±0.7	23.3±0.7
	0°	38.4±1.5	———	30.0±1.2	———
	15°	32.6±1.2	35.3±1.3	24.7±1.0	24.9±1.0
40 m	30°	29.7±1.2	32.6±1.3	20.6±0.9	20.2±0.7
	45°	26.5±1.0	29.5±1.2	16.5±0.6	16.5±0.6
	60°	24.5±0.9	25.9±1.0	13.3±0.6	13.3±0.6

TABLE II

Ellipticity and percentage asymmetry of extensive air showers

	Zenith angle Z	Average shower rate from E–W $x \pm \Sigma_x$	Average shower rate from N–S $y \pm \Sigma_y$	Ellipticity $\frac{x \pm \Sigma_x}{y \pm \Sigma_y}$	Percentage asymmetry $F = \frac{2(x-y)}{(x+y)} \times 100\%$
10 m	0°	94.4±1.8	87.0±1.6	1.09±.029	8.2±2.6
	15°	80.5±1.4	72.1±1.2	1.12±.027	11.0±2.4
	30°	72.3±1.2	62.1±1.1	1.16±.028	15.2±2.4
	45°	63.3±1.1	53.4±0.9	1.19±.029	17.0±2.4
	60°	54.5±1.0	46.5±0.9	1.17±.031	15.8±2.7
25 m	0°	58.9±1.4	52.5±1.1	1.12±.036	11.5±3.2
	15°	52.2±1.1	40.3±0.9	1.30±.040	25.7±3.0
	30°	46.6±0.9	33.3±0.7	1.40±.040	33.3±2.8
	45°	42.7±1.0	28.5±0.7	1.50±.051	39.9±3.3
	60°	36.1±0.8	22.9±0.5	1.58±.049	44.7±3.0
40 m	0°	38.4±1.1	30.0±0.9	1.28±.053	24.6±4.1
	15°	34.0±0.9	24.8±0.7	1.37±.053	31.3±3.8
	30°	31.2±0.9	20.4±0.6	1.53±.063	41.9±3.9
	45°	28.0±0.8	16.5±0.4	1.70±.064	51.7±3.5
	60°	25.2±0.7	13.3±0.4	1.89±.078	61.8±3.7

TABLE III

East-West percentage asymmetry of extensive air showers

Zenith angle Z	East-West asymmetry of extensive air showers		
	10 m:	25 m:	40 m:
0°	—	—	—
15°	2.61±3.34	10.34±4.32	7.95±5.38
30°	7.61±3.32	6.86±3.82	9.30±5.70
45°	9.01±3.57	11.70±4.45	10.71±5.53
60°	13.03±5.87	5.82±4.31	5.55±5.32

showers are distributed elliptically around the shower axis. The percentage asymmetry between the shower rates from E-W and N-S directions is given in the last column of Table II.

The errors in the ellipticity and the percentage asymmetries are calculated as follows :-

If (F) is a function of both x and y then the error in F is given by

$$\Sigma^2 = \left[\frac{d(F)}{dx}\right]^2 \Sigma_x^2 + \left[\frac{d(F)}{dy}\right]^2 \Sigma_y^2$$

where Σ_x and Σ_y are errors in (x) and (y), and Σ is the error in the function (F).

Then a graph is drawn with the zenith angles along the abscissa and the percentage asymmetries along the ordinate for the three separations of the telescopes. From the graph it is clear that there is a systematic increase in the asymmetry with zenith angle. It can also be seen that at any particular zenith angle the asymmetry increases with the separations of the telescopes. Of course the same arguments hold good for ellipticity also. The percentage asymmetry and elipticity will increase by about 4 or 5% if the counting rates of showers only from West and South are taken into consideration, because the average shower rate from *E-W* is less than the individual shower rate from West, though the shower rates from North or South are exactly the same.

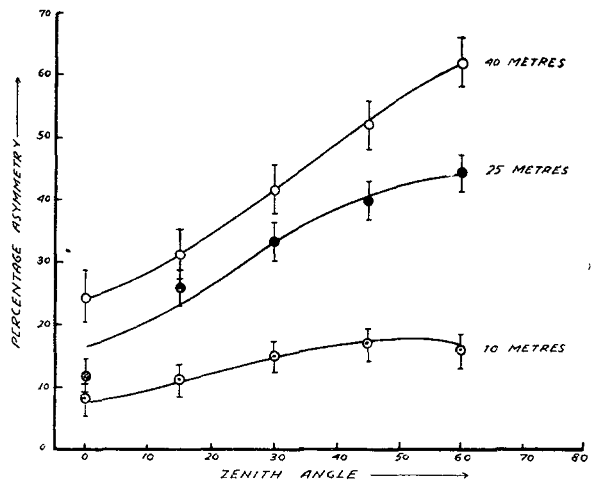

Fig. 2. **Zenith angle versus percentage asymmetry.**

Though the main aim of the investigation is to find out the geomagnetic effect on extensive air showers, there is one more interesting point. At all zenith angles from 15°-60° for the three separations 10 m, 25 m, and 40 m. the shower rate is slightly more from West than from East direction. This East-West asymmetry of extensive air showers is shown in Table III. In view of the very large statistical errors, and very poor angular resolution of the telescopes, it is felt better not to draw any definite conclusion. But it appears that there is some East-West asymmetry for extensive air showers also. From Table III it can be seen that for 10 m separation the asymmetry gradually increases from 15° to 60° zenith, whereas for 25 m, and 40 m, it reaches a maximum at 45° zenith and then comes down. To arrive at any conclusion regarding this East-West asymmetry of extensive air showers, more data are needed.

CONCLUSION

At moderate latitudes and mountain altitudes the geomagnetic field has a considerable and well detectable influence on the density distribution of extensive air showers. The percentage asymmetry between the shower rates from E-W and N-S increases not only with the separation of the two telescopes but also with the zenith angle at which the telescopes are inclined. There appears to be 5 to 10% East-West asymmetry also for Extensive air showers.

ACKNOWLEDGMENTS

One of the authors (A. B. Rao) wishes to thank 'The Scientific Research Committee, Government of U.P.' for the financial help he received under the scheme "The Study of Extensive Air Showers." He thanks all the staff and the scholars of Gulmarg Observatory for their friendly help and suggestions. His thanks are also due to Mr. Ajit Singh (Department of Physics, Muslim University, Aligarh) for his liberal co-operation while preparing the G. M. counters.

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Reprinted from the Indian Journal of Physics Vol. XXXV, No. 10, Nove ber 1961 pp. 568—572

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DIRECTIONAL PROPERTIES OF EXTENSIVE AIR SHOWER ARRAYS

A. BHASKARA RAO AND P. S. GILL

DEPARTMENT OF PHYSICS, MUSLIM UNIVERSITY, ALIGARH

(*Received July* 12, 1961)

ABSTRACT. The simple extensive air shower array proposed by Shen and Singer (1957) for which they claimed about 90% directional efficiency, has been tested by two groups of physicists, McCusker *et al.* (1959) and Layson *et al.* (1960), using it in conjunction with cloud chambers and scintillation counters, respectively. They concluded that the proposed set up has got very poor efficiency in selecting showers in preferred directions. It is pointed out that there are some significant differences between the results of various authors, on this problem and that it is possible to make further improvements in the performance of the device. besides the two methods suggested by McCusker *et al.* (1959).

INTRODUCTION

Shen and Singer (1957) proposed a simple extensive air shower array consisting of three G. M. counter telescopes, placed at the vertices of a triangle, for which they claimed a directional efficiency of 90%. This arrangement has been tested by McCuker *et al.*, (1959) using a similar unit in conjunction with two cloud chambers. From their experimental results they concluded that there is no great improvement in the angular resolution of the apparatus suggested by Shen and Singer, and it is not of much value in looking for anisotropy in the high energy primary cosmic radiation. Their results indicate that the vertical arrangement leads only to 7% (or at the best 14%) enrichment of showers coming from the near vertical direction. But our results (Bhaskara Rao and Gill, 1960), obtained during the course of an investigation on the influence of geomagnetic field on extensive air showers at Gulmarg, suggest an enrichment value of the order of 55%. With a view to check our Gulmarg data, a similar experiment has been conducted at Aligarh (alt. 680 ft.), again with two telescopes. The experimental results give an enrichment figure of 54% which is very high when compared to that of McCusker *et al.* Moreover, McCusker *et al.*, contented that there is no serious disagreement between their own results and those of Shen and Singer. Even this contention is not justifiable as shown at a latter stage. Further, their results are in disagreement not only with our results, but also with those of Shen and Singer and of Rathgeber (1959). Although the experimental results of Layson *et al.* (1960) agree well with their theoretical calculations, their shower data do not seem to follow the well established $\cos^n\theta$ law. Finally, whatever might be the actual directional efficiency and usefulness of the shower array proposed by Shen and Singer, the observed discrepancies are very significant and worth consideration. Further slight improvements can be made in the device.

EXPERIMENTAL

The arrangement used consisted of two G.M. counter telescopes of semiangle 10°, with two trays in each. Each tray consisted of four counters connected in parallel. The telescopes could be tilted independently around any axis. All other details of the experiment were exactly the same as mentioned in our paper (Bhaskara Rao and Gill, 1960).

The separation between the telescopes was 40*m*. Fourfold coincidences were recorded in the East-West and North-South planes, the telescopes being fixed in three positions, vertical, 45° zenith angle and horizontal, in rotation. The position of the telescopes was changed from the E-W plane to N-S plane and vice versa for every twenty days. The data were corrected for pressure and temperature variations using $\beta = -10\%$ cm^{-1}Hg.. and $\theta_T = -0.38\%$ per degree C, respectively. Then the average of the shower rates in the two planes was calculated.

RESULTS AND DISCUSSION

Here four instances are given, including our own results at Aligarh, to point out the large discrepancies between the results of various authors.

(A) The shower rates corresponding to 40 *m* separation of the telescopes were given in Table I.

TABLE I

Coincidence rate vs. zenith angle

Zenith angle '*Z*'	Average coincidence rate per hour
0°	4.98±0.08
45°	3.69±0.07
90°	2.30±0.06

$$\text{Percentage enrichment} = \frac{V-H}{V} \times 100\% = 54\%$$

Where V = Coincidence rate with telescopes in the vertical position,
H = Coincidence rate in the horizontal position.

Here it should be remembered that the experimental results of McCusker *et al.*, actually give only 7% enrichment which is very low when compared to our value of 54%.

(B) Some of the experimental results of Rathgeber,

TABLE II

Shower rate in counts per hour

Zenith angle 'Z'	Counters in each telescope.	
	(X) 2 counters	(Y) 3 counters
0°	1.96±0.29	1.56±0.27
90°	1.25±0.23	0.77±0.16

From the columns (X) and (Y), enrichment values can be calculated as 36% and 51% respectively. Evidently, there is large difference between the enrichment values of McCusker *et al.*, and Rathgeber.

(C) Comparison of the experimental results of Shen and Singher and McCusker *et al.*

TABLE III

Experimental determination of zenith angle distribution

Separation between the extreme counters in cms.	Effective zenith angle	Difference of effective zenith angle	Six fold coincidence rate per hour	Percentage difference in the coincidence rate.
		Shen and Singer		
(i) 46.2	6.3°	13.2°	0.30±0.020	
(ii) 14.8	19.5°		0.46±0.025	55%
		McCusker *et al.*,		
(i) 67.0	5.6°		0.605±0.039	
(ii) 15.0	24.8°	19.2°	0.692±0.029	14%

The experimental set up used by McCusker *et al.*, was just similar to that of Shen and Singer. Shen and Singers' results show a difference of 55% in the counting rate for a difference of 13.2° in the effective zenith angle, whereas those of McCusker *et al.*, show only a variation of 14% for 19.2° difference of effective zenith angle. In fact McCusker *et al.*, should have observed a difference larger than 55%. Moreover, McCusker *et al.*, contented that their experimental results are not in serious disagreement with those reported by Shen and Singer. From the above table it is easy to see how they are not justified in their contention.

(D) Experimental results of Layson *et al.*,(1960) :

The directional response of the same set up was also tested by Layson *et al.*, using it in conjunction with the Sydney air shower apparatus. Although they claim that their experimental results are in good agreement with their theoretical calculations, their data do not seem to follow the well known $\cos^n\theta$ law. The zenithal distribution of showers given by them in the form of histogram, (corresponding to all showers) is compared with the distribution obtained by McCusker *et al.*, with the help of cloud chambers. Even if the directional efficiency of the system were to be low the observed data should have followed the $\cos^n\theta$ law. Data obtained by McCusker, *et al.*, follows the theoretical distribution well, but the histogram given by Layson *et al.*. is much different from what it ought to be. From Fig. 1(b) it can be seen that the telescopic system records more showers at larger zenith angles (from 5°–40°, at an interval of 5°) than from the vertical and near vertical i.e., 0°–5°. In particular *the shower rate at 20°—25° is four times* the rate at 0°–5°. This discrepancy is of very serious nature, which requires

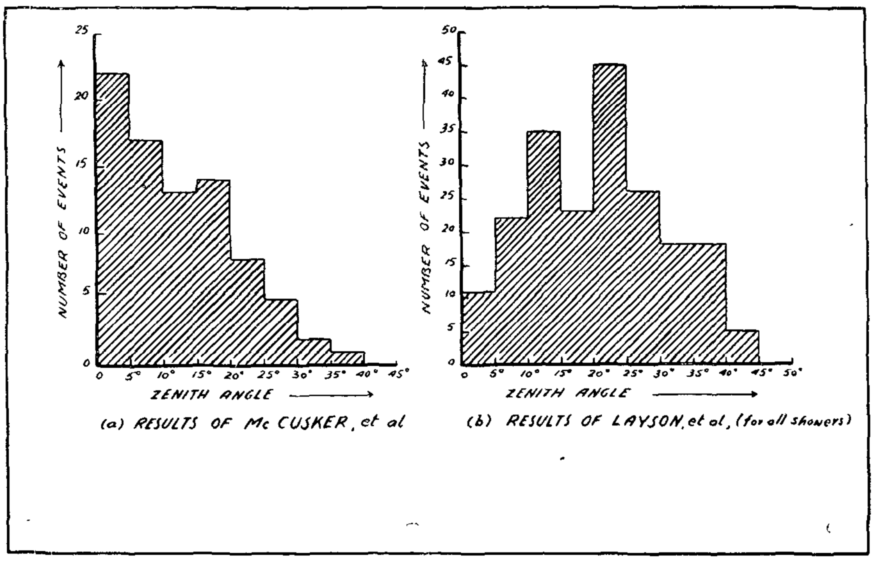

Fig. 1. The frequency of showers of different zenith angles setting off the arrangement.

some explanation. Rossi (1960) attributed the flat distribution of showers observed at Alto (alt. 4100m; shower size ($10^7 < N < 3\times10^7$) to the fact that the showers are still near their maximum development. But the same arguments cannot hold good in the case of showers recorded at Sydney.

In view of the significant discrepancies in the experimental results of McCusker *et al.*, and other workers, and the irregularities of basic value in the zenithal distribution of showers recorded by Layson *et al.*, one should be cautious in drawing a quantitative conclusion regarding the directional efficiency of the shower array. It is to be emphasized that the directional efficiency of an array decreases at larger zenith angles because of the nonuniformity of the side shower background. McCusker *et al.*, suggested two ways to improve the performance of the device. This can be still improved by using sets of two or more counters connected in parallel, in the telescopes, instead of single counters, at the same time keeping the aperture of the telescopes constant by adjusting the separation between the upper and lower sets suitably. This offers larger sensitive area for shower particles coming within the defined aperture of the telescopes and helps in reducing the percentage background of side showers from zenith angles, other than the defined aperture, in which we are not interested. This background can also be reduced by increasing the multiplicity of coincidence from six to nine, with a third set of counters in between the upper and lower sets of each telescope. These modifications do not have any significant effect on shower particles falling within the defined angle, but considerably reduce the background.

ACKNOWLEDGMENT

One of the authors (A. B. R.) wishes to acknowledge with thanks the valuable discussions he had with Dr. D. E. Page and Dr. B. V. Sreekantan through correspondence. His thanks are also due to the University authorities for the financial help.

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